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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR §1.53(c).

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INVENTOR(S)		
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TITLE OF THE INVENTION (500 characters max)

Acquiring Information of Optical Inhomogeneity and Other Properties in Substances

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OR

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Address					
Address					
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ENCLOSED APPLICATION PARTS *(check all that apply)*

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[] Application Data Sheet. See 37 CFR 1.76.

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

[X] No.

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Respectfully submitted,

Signature

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PROVISIONAL APPLICATION FOR PATENT

under

37 CFR §1.53(c)

TITLE: ACQUIRING INFORMATION OF OPTICAL INHOMOGENEITY AND OTHER PROPERTIES IN SUBSTANCES

APPLICANT: FEILING WANG

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Acquiring Information of Optical Inhomogeneity and Other Properties in Substances

Background

[0001] This application relates to non-invasive, optical probing of various substances, including but not limited to skins, body tissues and organs of humans and animals.

[0002] Investigation of substances by non-invasive and optical means has been the object of many studies as inhomogeneity of light-matter interactions in substances can reveal their structural, compositional, physiological and biological information. Various devices and techniques based on optical coherence domain reflectometry (OCDR) may be used for non-invasive optical probing of various substances, including but not limited to skins, body tissues and organs of humans and animals, to provide tomographic measurements of these substances.

[0003] In many OCDR systems, a light source of broad spectral distribution, often termed as broadband source, low-coherence source, partially coherent source or white light source, is generally employed. Referring to Fig. 1, a conventional approach is to split the radiation of the source into two paths, one propagating to impinge on the substances under study, or sample, while the other propagating towards a reference surface. The radiations reflected from the sample and from the reference

surface are then brought back to the same space and let interfere. Because of the wavelength-dependent phase delay the interference results in no observable interference fringes unless the two optical path lengths of the split radiations are very similar, a physical mechanism for ranging. If the same device is used for both splitting and recombining the radiation we speak of a Michelson interferometer. The discoveries and the theories of the interference of partially coherent light is summarized by Born and Wolf in "Principles of Optics", Pergamon Press, 1980.

Prior Art

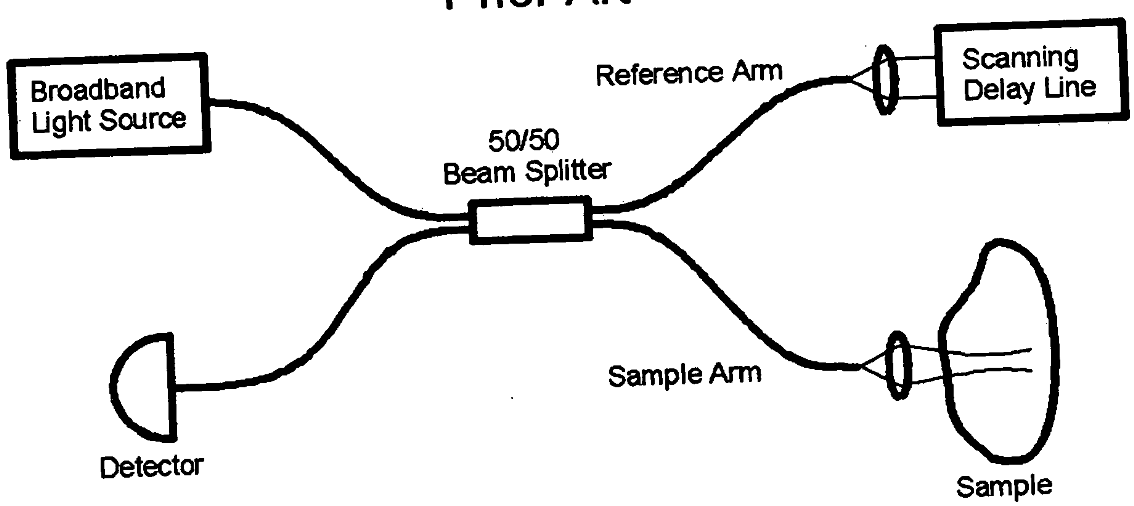


Fig. 1

[0004] Low-coherence light in free-space Michelson interferometers was first utilized for measurement purposes. With the advent of optical fibers modern interferometers are often constructed with fiber-optic components, leading to flexible application of low-coherence light as means of characterizing substances. Various embodiments of the fiber-optic OCDR exist such as what is disclosed by Sorin et al in US Patent No. 5,202,745, by Marcus et al in US Patent No. 5,659,392, by Mandella et al in US Patent No. 6,252,666, and by Tearney et al in US Patent No. 6,421,164. The application of OCDR in medical diagnoses has come to known as "optical coherence tomography", or OCT.

[0005] Common to most of these and other implementations, the radiation from the low-coherence source is first physically parted to have two portions, one traveling down a sample waveguide to interact with the sample while the other traveling down a reference waveguide. The reflected radiation from the sample is later recombined with the reference light from the reference waveguide and let interfere, as typified by the arrangement described in US Patent 6,421,164.

Summary

[0006] The designs, techniques and exemplary implementations for non-invasive optical probing described in this application use the superposition and interplay of different optical waves and modes propagating along substantially the same optical path inside one or more common optical waveguides. When one of the optical waves or modes interacts with the substance under study its superposition with another wave or mode can be used for the purpose of acquiring information about the optical properties of the substance.

[0007] The methods and apparatus described in this application are at least in part based on the recognition of various technical issues and challenges, practical considerations in implementing OCDR in commercially practical and user friendly apparatus, and various technical limitations in OCDR systems disclosed by the above referenced patents and in other publications. As an example, at least one of disadvantages associated to the OCDR system designs shown in Fig. 1 or described in the aforementioned patents is the separation of the reference light beam from the sample light beam. Due to the separation of the optical paths, the relative optical phase or differential delay between the two beams may experience uncontrolled fluctuations and variations, such as different physical length, vibration, temperature, waveguide bending and

so on. When the sample arm is in the form of a fiber-based catheter, in particular, the manipulation of the fiber may cause a significant fluctuation and drift of the differential phase. This lack of stable differential phase between the two beam may lead to technical difficulties in phase sensitive measurements as absolute valuation of refractive indices and measurements of birefringence.

[0008] In various examples described in this application,optical radiation is not physically separated to travel different paths. Instead, all propagation waves and modes are guided along essentially the same optical path through one or more common optical waveguides. Such designs with the common optical path may be advantageously used to stabilize the relative phase among different radiation waves and modes in the presence of environmental fluctuations in the system such as variations in temperatures, physical movements of the system especially of the waveguides, and vibrations and acoustic impacts to the waveguides and system. This is in contrast to some other interferometers in which sample light and reference light travel in different optical paths, prone to noise caused by the variation in the differential optical path. The stability of the differential optical path, achieved in the invented system, is beneficial for some phase-sensitive measurement, such as the

determination of the absolute reflection phase and birefringence.

[0009] In various applications, it may be beneficial to acquire the absorption characteristics of the material in an isolated volume inside the sample. In other case it may be desirable to map the distribution of some substances identifiable through their characteristic spectral absorbance. In some OCDR systems such as systems in aforementioned patents, it may be difficult to perform direct measurements of the optical inhomogeneity with regard to these and other spectral characteristics. The systems and techniques described in this application may be configured to allow for direct measurements of these and other spectral characteristics of a sample.

[0010] Some implementations are listed below as examples.

1. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a light source,

b) a waveguide that is capable of supporting at least two independent propagation modes, said waveguide carrying the light radiation from said light source to the vicinity of a sample under examination,

c) a probe head that terminates said waveguide in the vicinity of said sample and reverses the propagation direction of a first

mode in said waveguide while transmitting a second mode to said sample,

d) a differential delay modulator that varies the relative optical path length between said first mode and said second mode supported by said waveguide,

e) a mode combiner that superposes said first mode and said second mode by converting a portion of each said mode to a pair of new modes,

f) a photo-detector or a plurality of photodetectors,

g) an electronic controller in communication with said probe head, said differential delay modulator and said photo-detectors.

2. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a light source that emits radiation to excite two independent propagation modes in a first waveguide capable of supporting at lease two independent propagation modes,

b) a light director that terminates the first waveguide with a first port and passes the light modes entering said first port, at least in part, through a second port and passes the light modes entering said second port, at least in part, through a third port,

c) a second waveguide that supports at least two independent propagation modes and links the second port of the light director to

d) a probe head that terminates the second waveguide and, in the vicinity of the sample, reverse the propagation direction of one mode while reshaping and delivering the other mode to the sample and gathering the reflected light from the sample back into the second waveguide,

e) a differential delay modulator that connects to the third port of the light director through a third waveguide capable of supporting at least two independent propagation modes and imposes a variable path length and a variable phase delay on one mode relative to the other before conveying both modes, through a fourth waveguide capable of supporting at least two independent modes, to

f) a detection subsystem that superposes the two propagation modes from the differential delay modulator to form two new modes, mutually orthogonal; said two new modes are terminated by two photo-detectors.

3. The apparatus of Claim 2 wherein all the four waveguides are polarization-maintaining optical fibers capable of supporting two orthogonal polarization modes.

4. The apparatus of Claim 2 wherein the first, the third and the fourth waveguides are free space while the second waveguide is a polarization-maintaining optical fiber capable of supporting two orthogonal polarization modes.

5. The apparatus of Claim 2 wherein all waveguides are free space.

6. The apparatus of Claim 2 wherein the probe head comprises a lens, a polarizing beam splitter and a reflector, arranged in such a way that said polarizing beam splitter diverts a first polarization mode to a reflector, causing it to re-enter the second waveguide, while transmitting a second polarization mode to the sample and collecting the reflected radiation from the sample back the second waveguide.

7. The apparatus of Claim 2 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

8. The apparatus of Claim 2 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

9. The apparatus of Claim 8 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

10. The apparatus of Claim 8 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

11. The apparatus of Claim 8 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

12. The apparatus of Claim 2 wherein the light director is a polarization-preserving circulator that conveys the independent modes supported by the first waveguide to the corresponding independent modes supported by the second waveguide without substantial mixing or cross coupling of modes and conveys the independent modes supported by the second waveguide to the corresponding independent modes supported by the third waveguide without substantial mixing or cross coupling of modes.

13. The apparatus of Claim 2 wherein the light director is a polarization insensitive beam splitter.

14. The apparatus of Claim 2 wherein the detection subsystem comprises a polarizing beam splitter and two photo-detectors, said polarizing beam splitter oriented in such a way that each split radiation is a superposition of the two independent propagation modes in the fourth waveguide and is received by a photo-detector.

15. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a broadband and polarized light source that is optically coupled to a first polarization-maintaining fiber capable of supporting two orthogonal polarization modes,

b) a three-port polarization-preserving circulator that relays two orthogonal polarization modes entering a first port to a second port while relaying two orthogonal polarization modes entering said second port to a third port, said first port terminating the first polarization-maintaining fiber,

c) a second polarization-maintaining fiber that supports two orthogonal polarization modes; said second polarization-maintaining fiber is terminated at one end by the second port of the polarization-preserving circulator and at the other by

d) a probe head that comprises a lens, a polarizing beam splitter and a retroreflector, arranged in such a way that said polarizing beam splitter reverses the propagation direction of one polarization mode by diverting it to said retroreflector while reshaping and delivering the other polarization mode to the sample and gathering the reflected light from the sample back the second polarization-maintaining fiber,

e) a differential delay modulator that imposes a variable path length and a variable phase delay on one propagation mode in

reference to the other; said differential delay modulator is linked at one end to the third port of the light director and at the other to

f) a detection subsystem comprising a polarizing beam splitter and two photo-detectors; said polarizing beam splitter oriented in such a way that each split light wave is a superposition of the two polarization modes leaving the third port of the polarization-preserving circulator and is received by a photo-detector.

16. The apparatus of Claim 15 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

17. The apparatus of Claim 15 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

18. The apparatus of Claim 17 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

19. The apparatus of Claim 17 wherein the variable path length device comprises two collimators both facing a mechanically movable

retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

20. The apparatus of Claim 17 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

21. An apparatus for acquiring information of optical inhomogeneity in substances, said apparatus comprising:

a) a light source,

b) a waveguide that is capable of supporting at least two independent propagation modes, said waveguide carrying the light radiation from said light source to the vicinity of a sample under examination,

c) a probe head that terminates said waveguide in the vicinity of said sample and reverses the propagation direction of a portion of a first mode in said waveguide while transmitting the remainder to said sample meanwhile converting the reflected light collected from said sample to a second propagation mode,

d) a differential delay modulator that varies the relative optical path length between said first mode and said second mode supported by said waveguide,

e) a mode combiner that superposes said first mode and said second mode by converting a portion of each said mode to a pair of new modes,

f) a photo-detector or a plurality of photodetectors,

g) an electronic controller in communication with said probe head, said differential delay modulator and said photo-detectors.

22. An apparatus for acquiring distribution of optical inhomogeneity in substances, said apparatus comprising:

a) a light source that emits radiation to excite a propagation mode in a first waveguide capable of maintaining the mode,

b) a light director that terminates the first waveguide with its first port and passes the light mode entering said first port, at least in part, through a second port and passes the light modes entering said second port, at least in part, through a third port,

c) a second waveguide that supports at least two independent propagation modes and links the second port of the light director to

d) a probe head that reverses the propagation direction of the light in part and transmits the remainder to the sample meanwhile transforming the collected light from the sample

reflection to an orthogonal mode supported by the second waveguide,

e) a differential delay modulator that connects to the third port of the light director through a third waveguide capable of supporting at least two independent propagation modes and imposes a variable phase delay and a variable path length on one mode in reference to the other before conveying both modes, through a fourth waveguide capable of supporting at least two independent modes, to

f) a detection subsystem that superposes the two propagation modes from the fourth waveguide to form two new modes, mutually orthogonal; said two new modes are terminated by two photo-detectors.

23. The apparatus of Claim 22 wherein all the four waveguides are polarization-maintaining optical fibers capable of supporting two orthogonal polarization modes.

24. The apparatus of Claim 22 wherein the first, third and fourth waveguides are free space while the second waveguide is a polarization-maintaining optical fiber capable of supporting two orthogonal polarization modes.

25. The apparatus of Claim 22 wherein all waveguides are free space.

26. The apparatus of Claim 22 wherein the probe head consists of an uncoated or coated termination of a polarization-maintaining fiber to

have a finite reflectance, a lens and a quarter-wave plate or a Faraday rotator, all in a series.

27. The apparatus of Claim 22 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

28. The apparatus of Claim 22 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

29. The apparatus of Claim 28 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

30. The apparatus of Claim 28 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

31. The apparatus of Claim 28 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

32. The apparatus of Claim 22 wherein the light director is a polarization-preserving circulator that conveys a mode supported by the first waveguide to one of the modes supported by the second waveguide and conveys the independent modes supported by the second waveguide to the corresponding independent modes supported by the third waveguide.

33. The apparatus of claim 22 wherein the light director comprises:

a) a polarization-maintaining circulator that conveys a polarization mode entering a first port to a second port, causing no change in the state of polarization, and conveys the polarization mode entering said second port to a third port, causing no change in the state of polarization,

b) a first polarizing beam splitter that is connected to the second port of the polarization-maintaining circulator and separates the light into two different paths by state of polarization, and

c) a second polarizing beam splitter that is connected to the third port of the polarization-maintaining circulator and separates the light into two different paths by state of polarization.

34. The apparatus of Claim 22 wherein the light director is a polarization-insensitive beam splitter.

35. The apparatus of Claim 22 wherein the detection subsystem comprises a polarizing beam splitter oriented in such a way that each split

radiation is a superposition of the two independent propagation modes in the fourth waveguide and is received by a photo-detector.

36. An apparatus for acquiring distribution of optical inhomogeneity in substances, said apparatus comprising:

a) a broadband and polarized light source that is optically coupled to one of the polarization modes supported by a first polarization-maintaining fiber,

b) a polarization-preserving circulator that conveys a polarization mode entering a first port linked to the first polarization-maintaining fiber to a second port linkable to a polarization-maintaining fiber and conveys two orthogonal polarization modes entering said second port to a third port linkable to a polarization maintaining fiber without appreciable mode mixing or coupling,

c) a second polarization-maintaining fiber that supports two orthogonal polarization modes; said second polarization-maintaining fiber is terminated at one end by the second port of the polarization-preserving circulator and at the other by

d) a probe head that comprises an uncoated or coated termination of the second polarization-maintaining fiber to have a finite reflectance, a lens and a quarter-wave plate or a Faraday rotator arranged in a series,

e) a differential delay modulator that imposes a variable path length and a variable phase delay on one propagation mode in reference to the other; said differential delay modulator is linked at one end to the third port of the light director and at the other to

f) a detection subsystem comprising a polarizing beam splitter and two photo-detectors; said polarizing beam splitter oriented in such a way that each split light wave is a superposition of the two polarization modes leaving the third port of the polarization-preserving circulator and is received by a photo-detector.

37. The apparatus of Claim 36 wherein the differential delay modulator consists of one or more segments of such tunable birefringent materials as liquid crystal materials and lithium niobate crystals in conjunction with such fixed birefringent materials as quartz and rutile.

38. The apparatus of Claim 36 wherein the differential delay modulator comprises a means of separating the radiation by modes and directing one through a fix path while directing the other through a variable path length device.

39. The apparatus of Claim 38 wherein the variable path length device is a piezoelectric stretcher of a polarization-maintaining optical fiber.

40. The apparatus of Claim 38 wherein the variable path length device comprises two collimators both facing a mechanically movable retroreflector in such a way that the collimated light from one collimator is collected by the other through a trip to and from the retroreflector.

41. The apparatus of Claim 38 wherein the variable path length device comprises two collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

42. The apparatus of Claim 1, further comprising a tunable band pass filter, inserted in one of the four waveguides.

43. The apparatus of Claim 2, further comprising a tunable band pass filter, inserted in one of the four waveguides.

44. The apparatus of Claim 15, further comprising a tunable band pass filter, inserted in one of the four polarization-maintaining fibers.

45. The apparatus of Claim 21, further comprising a tunable band pass filter, inserted in one of the four waveguides.

46. The apparatus of Claim 22, further comprising a tunable band pass filter, inserted in one of the four waveguides.

47. The apparatus of Claim 36, further comprising a tunable band pass filter, inserted in one of the four polarization-maintaining fibers.

48. The apparatus of Claim 43 wherein the source spectrum covers some characteristic absorption peaks of glucose in an

infrared wavelength range for the determination of glucose concentration in the dermis layer of human skin.

49. The apparatus of Claim 46 wherein the source spectrum covers some characteristic absorption peaks of glucose in an infrared wavelength range for the determination of glucose concentration in the dermis layer of human skin.

[0011] Exemplary implementations are described below to illustrate various features and advantages of the systems and techniques. One of such features is methods and apparatus for acquiring information regarding optical inhomogeneity in substance by a non-invasive means with the help of a low-coherence radiation. Another feature is to achieve high signal stability and high signal-to-noise ratio by eliminating the need of splitting the light radiation into a sample path and a reference path. Addition features include, for example, a platform on which phase-resolved measurements such as birefringence and absolute refractive indices can be made, capability of acquiring optical inhomogeneity with regard to the spectral absorbance, solving the problem of signal drifting and fading caused by the polarization variation in conventional interferometers, and an effective use of the source radiation with simple optical arrangements. The advantages of enhanced performance and apparatus reliability, simplified operation and maintenance, simplified optical layout, reduced apparatus

complexity, reduced manufacturing complexity and cost, and others may be achieved by the systems and techniques described here.

[0012] These and other features, system configurations, associated advantages, and implementation variations are described in detail in the following drawings, textual description, and claims.

Detailed Description

[0013] Fig. 2 shows one example of a system for acquiring information of optical inhomogeneity in substances. Light radiation from broadband light source **201** is coupled into the first dual-mode waveguide **271** to excite two orthogonal propagation modes, **001** and **002**. Light director **210** directs the two modes to the second dual-mode waveguide **272** that is terminated by probe head **220**. The first function of the probe head is to reverse the propagation direction of mode **001** in waveguide **272**; the second function of the probe head is to reshape and delivered the light in mode **002** to the sample **205** which may be placed on a sample holder; and the third function of the probe head is to collect the light reflected from the sample back the second dual-mode waveguide **272**. The back traveling light in both modes is then directed by light director **210** to the third waveguide **273** and further propagates towards differential delay modulator **250**. The differential delay modulator is capable of varying the relative optical path length and optical phase between mode **001** and **002**. Finally detection subsystem **260** superpose the two propagation modes to form two new modes, mutually orthogonal, to be received by photo-detectors.

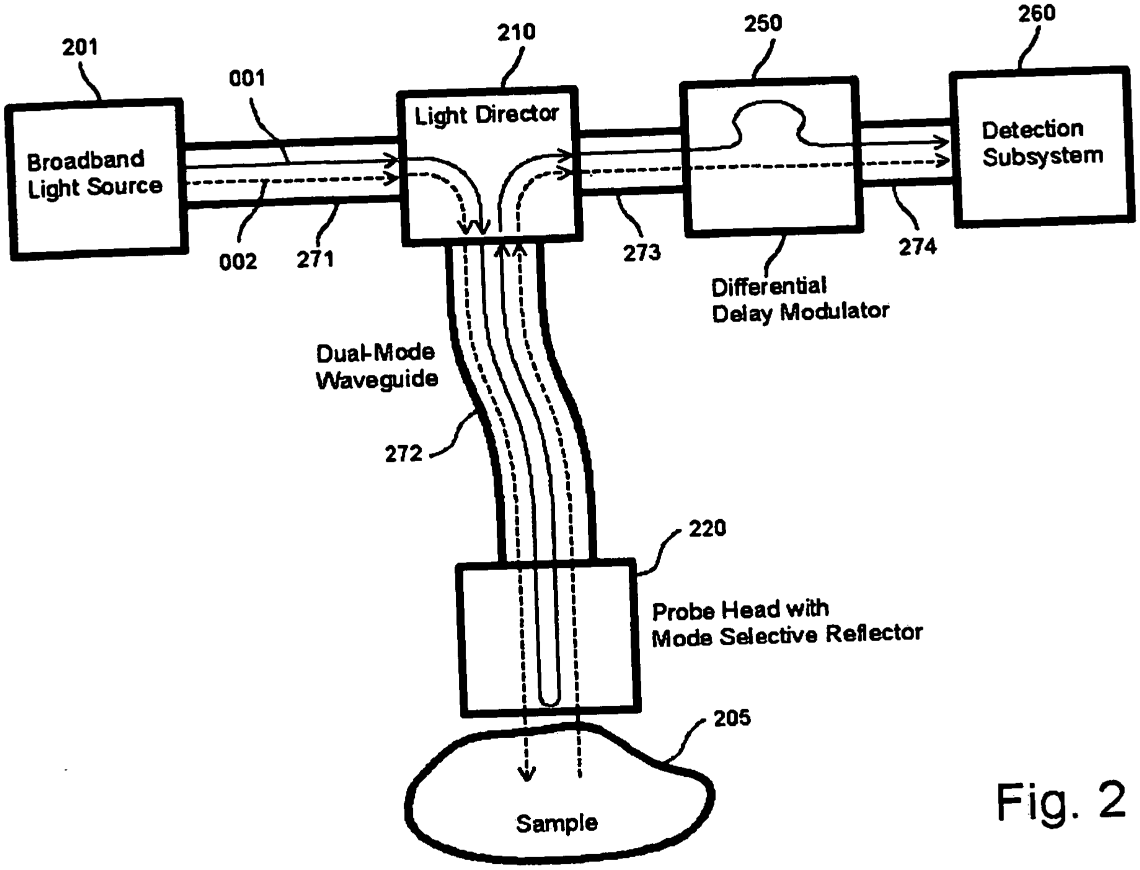


Fig. 2

[0014] In the example shown in Fig. 2, the superposition of the two modes in the detection subsystem allows range detection. The light entering the detection subsystem in mode **002** is reflected by the sample, bearing information about the optical inhomogeneity of the sample, while the other mode, **001**, bypassing the sample inside probe head **220**. So long as these two mode remain independent through the waveguides their superposition in the detection subsystem yields the same information about the sample as with a conventional Michelson interferometer.

[0015] For the simplicity of the analysis, let us first consider a thin slice of the source spectrum by assuming that the amplitude of mode **001** is E_{001} and that of mode **002** is E_{002} in the first waveguide **271**. The sample can be characterized by an effective reflection coefficient r that is complex in nature; the differential delay modulator **350** can be characterized by a pure phase shift Γ exerted on mode **001**. Let us now superpose the two modes by projecting them onto a pair of new modes, represented by a 45 degree rotation in the vector space, we get

$$\begin{cases} E_A = \frac{1}{\sqrt{2}}(e^{j\Gamma} E_{001} + rE_{002}); \\ E_B = \frac{1}{\sqrt{2}}(e^{j\Gamma} E_{001} - rE_{002}). \end{cases} \tag{1}$$

In deriving the above equation it has been assumed that all components in the system, except for the sample, are lossless. The resultant intensities of the two superposed modes are

$$\begin{cases} I_A = \frac{1}{2}\left[E_{001}^2 + E_{002}^2 + |r| E_{001}E_{002}\cos(\Gamma - \varphi)\right]; \\ I_B = \frac{1}{2}\left[E_{001}^2 + E_{002}^2 - |r| E_{001}E_{002}\cos(\Gamma - \varphi)\right], \end{cases} \tag{2}$$

where φ is the phase delay associated with the reflection from the sample. A convenient way to characterize the reflection coefficient r is to measure the difference of the above two intensities, i.e.

$$I_A - I_B = |r| E_{001}E_{002}\cos(\Gamma - \varphi) . \tag{3}$$

If Γ is modulated by differential delay modulator **250**, the measured signal, Eq. (3), is modulated accordingly. For either a periodic or a time-linear variation of Γ, the measured responds with a periodic oscillation, its peak-to-peak value being proportional to the absolute value of r.

[0016] For a broadband light source, we must consider the two phases, Γ and φ, wavelength dependent. If the two modes experience significantly different path lengths when they reach the detection system, the overall phase angle, $\Gamma - \varphi$, must be significantly wavelength dependant as well. Consequently the measured signal, being an integration of Eq. (3) over the source spectrum, yields a smooth function even though Γ is being varied. The only condition for a significant oscillation to occur in the measured signal is when the two modes experience very similar path lengths at the point of their superposition. In this case the overall phase angle, $\Gamma - \varphi$, becomes wavelength independent or nearly wavelength independent. In other words, for a given relative path length set by the modulator 250, an oscillation in the measured signal indicates a reflection, in the other mode, from a distance that equalizes the optical path lengths traveled by the two modes. Therefore the system depicted in Fig. 2 can be utilized for ranging reflection sources.

[0017] Due to the stability of relative phase between the two modes, 001 and 002, phase-sensitive measurements can be performed with the invented system with relative ease. The following describes a scheme for the determination of the absolute phase associated with the radiation reflected from the sample.

[0018] The scheme involves generating a sinusoidal modulation in the differential phase by means of differential delay modulator 250, with magnitude M and frequency Ω, so that we can rewrite the measured as follows:

$$I_A - I_B = |r| E_{001} E_{002} \cos[M \sin(\Omega t) - \varphi] \,. \tag{4}$$

It is clear from Eq. (4) that the measured exhibits an oscillation form that contains a base frequency of Ω and its harmonics. The amplitudes of the base frequency and each of the harmonics are related to φ and $|r|$. It is straightforward to derive the mathematical expressions for the relationships between r and the harmonics. For instance, the amplitude of the base-frequency oscillation and the second harmonic can be found from Eq. (4) to be:

$$A_{\Omega} = E_{001} E_{002} J_1(M) |r| \sin\varphi \,; \tag{5a}$$

$$A_{2\Omega} = E_{001} E_{002} J_2(M) |r| \cos\varphi \,, \tag{5b}$$

where J_1 and J_2 are Bessel functions of the first and second order, respectively. From Eq. (5a) and (5b) one can solve for

$|r|$ and φ, i.e. the complete characterization of r. We can therefore completely characterize the complex reflection coefficient r by analyzing the harmonic content of various orders in the measured signal. In particular, the presence of the base-frequency component in the measured is due to the presence of φ.

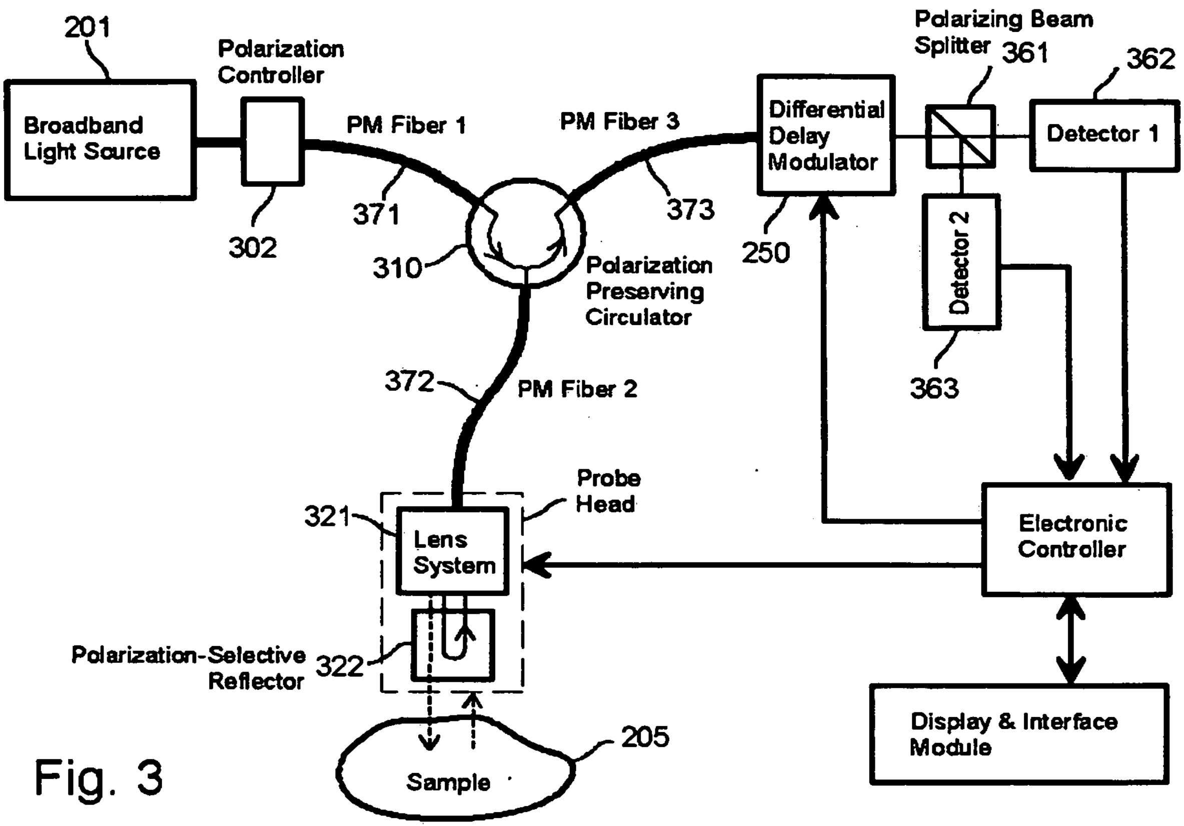


Fig. 3

[0019] An implementation of the system depicted in Fig. 2 is shown in Fig. 3. The spectrum of source 201 should be chosen to satisfy the desired ranging resolution. The broader the spectrum

is the better the ranging resolution. Some semiconductor superluminescent light emitting diodes (SLED) and amplified spontaneous emission (ASE) sources may possess the appropriate spectral properties for the purpose. Polarization controller 302 is used to control the state of polarization in order to proportion the magnitudes of the two modes, 001 and 002, in waveguide 371. Dual-mode waveguides 371, 372 and 373 are capable of supporting two independent polarization modes which are mutually orthogonal. One kind of practical and commercially available waveguide is the polarization maintaining optical fiber. A polarization maintaining fiber can carry two independent polarization modes, namely, the s-wave polarized along its slow axis and the p-wave polarized along its fast axis. In good quality polarization maintaining fibers these two modes have virtually no energy exchange, or coupling, for very substantial distances. Polarization preserving circulator 310 directs the flow of optical waves according to the following scheme: the two incoming polarization modes from fiber 371 are directs to fiber 372; the two incoming polarization modes from fiber 372 are directed to fiber 373. Polarization-preserving circulator 310 is ideally required to maintain the separation of the two independent polarization modes. For instance, the s-wave in fiber 371 should be directed to fiber 372 as s-wave or p-wave

only. Certain commercially available polarization-preserving circulators are adequate for the purpose.

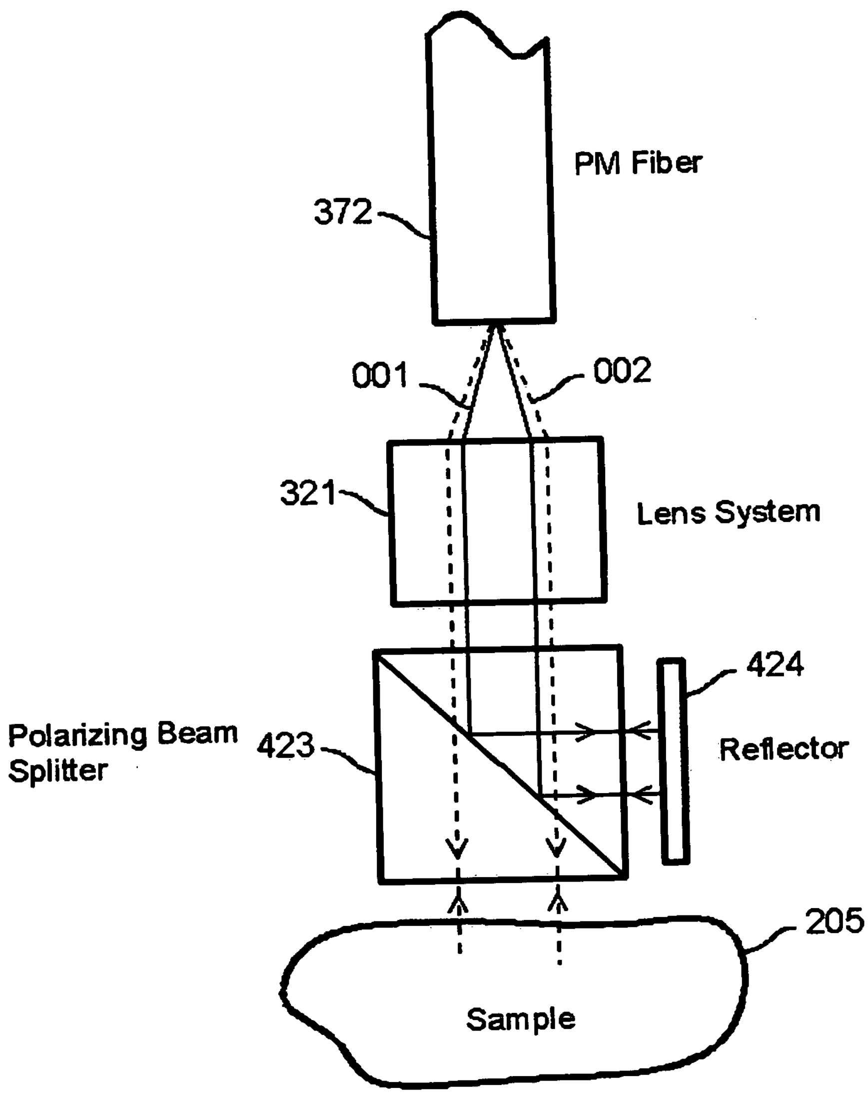


Fig. 4

[0020] The details of the probe head is shown in Fig. 4. Lens system 321 is to concentrate the light energy into a small area, facilitating spatially resolved studies of the sample in a lateral direction. Polarizing beam splitter 423 is used to

transmit radiation in one polarization mode, 002 shown, to the sample while diverting the other to reflector 424, that can be simply a coating on one side of beam splitter 423. Reflector 424 should be aligned to allow the reflected radiation to re-enter polarization-maintaining fiber 372.

[0021] A number of hardware choices are available for differential delay modulator **250**, either mechanical or non-mechanical. A non-mechanical type may consist of one or more segments of tunable birefringent materials such as liquid crystal materials and lithium niobate crystals in conjunction with fixed birefringent materials such as quartz and rutile. A mechanical device can be constructed by first separating the radiation by polarization mode with a polarizing beam splitter, one polarization mode propagating through a fix path while the other propagating through a variable path consisting of a piezoelectric stretcher of polarization maintaining fibers, or a pair of collimators both facing a mechanically movable retroreflector in such a way that the light from one collimator is collected by the other through a trip to and from the retroreflector, or a pair collimators optically linked through double passing a rotatable optical plate and bouncing off a reflector.

[0022] Superposition of the two independent polarization modes in the detection subsystem occurs when the two modes reach

polarization beam splitter **361**. Beam splitter **361** is preferably oriented in such a way that, for each independent polarization mode, the two split portions possess the same amplitude. This way, each photo-detector receives a superposed mode characterized by Eq. (1). This can be accomplished by rotating polarizing beam splitter **361** so that the incident plane of its reflection surface make a 45 degree angle with one of the two independent polarization mode, **001** or **002**.

[0023] To use the above-mentioned optical system for measuring and displaying the optical inhomogeneity of a substance one needs to add control electronics. Differential delay modulator **250**, under the control of the electronics and programs, generates a form of differential phase modulation as the differential path length scans through a range that matches a range of depth inside the sample. The electronic controller is also programmed to record and extract the amplitude of the oscillation in the measured signal characterized by Eq. (3) at various differential path lengths generated by **250**. One thus acquires a profile of reflection as a function of depth, a one-dimensional representation of sample inhomogeneity.

[0024] For acquiring two-dimensional images of optical inhomogeneity in the sample, the probe head should be controlled so that the probing light scans in a lateral direction, perpendicular to the light propagation direction. For every

increment of the lateral scan a profile of reflection as a function of depth can be recorded with the method described above. The collected information can then be displayed to form a cross-sectional image that reveals the inhomogeneity of the sample.

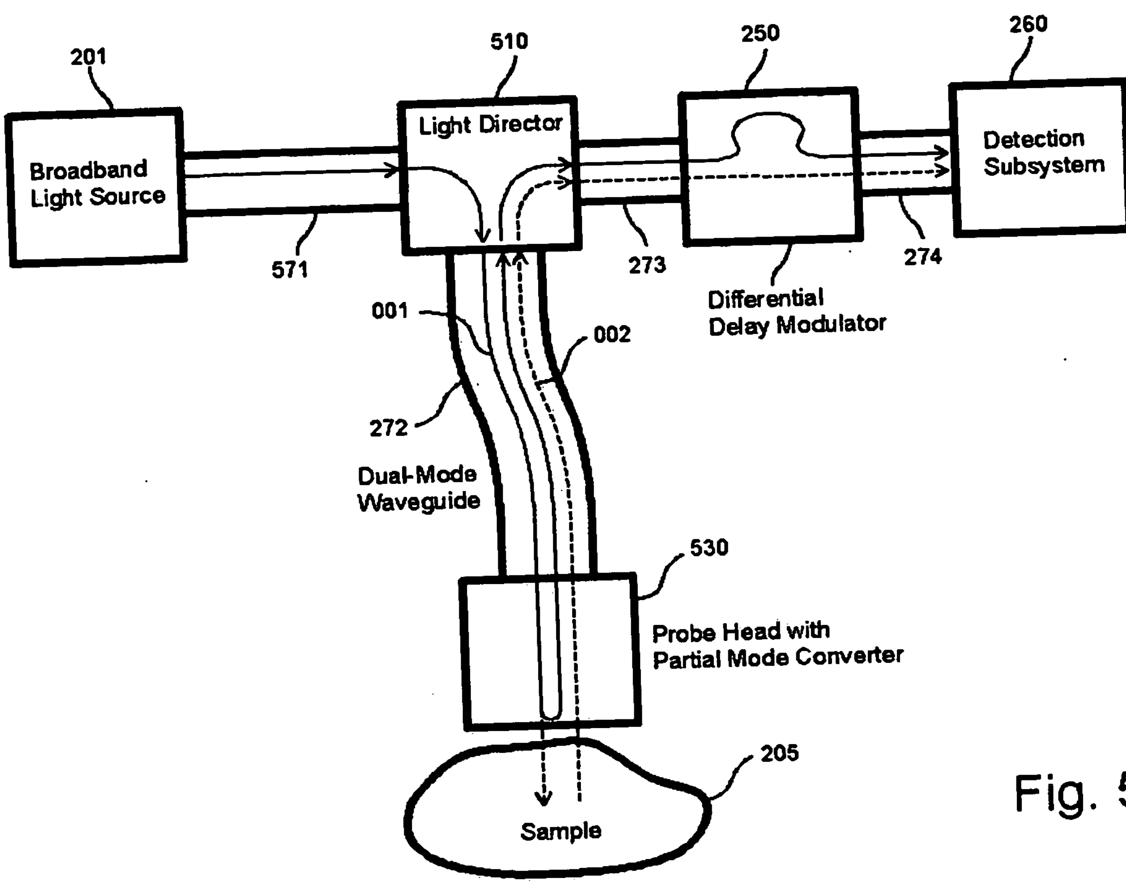


Fig. 5

[0025] Alternative to the design shown in Fig. 2, the optical arrangement depicted in Fig. 5 can be utilized for the same purpose. In this arrangement radiation from light source **201** is

coupled to one mode supported by mode maintaining waveguide 571. Light director 510 serves similar functions as 210 to convey the mode from 571 to one of the two modes supported by dual-mode waveguide 271. Dual-mode waveguide 271 is terminated at the other end by probe head 530 that performs these functions: a) to reverse the propagation direction of a small portion of the incoming radiation in mode 001; b) to reshape the remaining radiation and transmit it to the sample; and c) to convert the radiation reflected from the sample to an independent mode, 002 shown, supported by dual-mode waveguide 272. Now there are two modes propagating away from the probe head, mode 001 that bypasses the sample and mode 002 that originates from sample reflection, in complete analogy to what occurs in the system shown in Fig. 2. The rest of components in this system also function the same way as their counterparts in Fig. 2.

[0026] This alternative design, shown in Fig.5, can be implemented with practical components in an arrangement depicted by Fig. 6. Radiation from broadband light source 205 is further polarized and controlled by polarization controller 602 so that a polarization mode is excited in polarization-maintaining fiber 371. Light director 610 conveys the polarization mode to one of the two polarization modes supported by polarization-maintaining fiber 372. This mode further propagates towards the probe head 530.

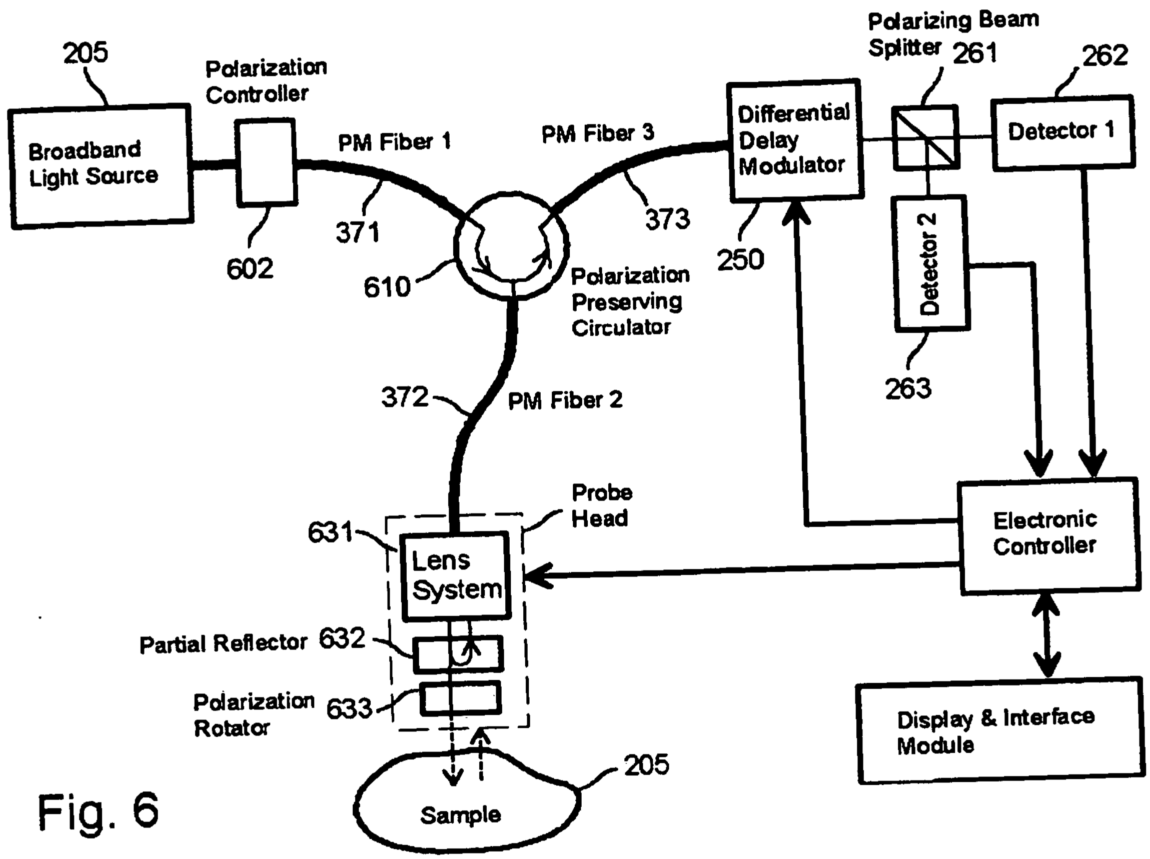


Fig. 6

[0027] One of the possible designs for the probe head 530 is depicted Fig. 7. In this design, the termination of polarization-maintaining fiber 372 is used as partial reflector 632. An uncoated termination of an optical fiber reflects approximately 4% of the light energy. Coatings can be used to alter the reflectivity of the termination to a desirable value. Lens system 731 reshapes and delivers the remaining radiation to sample 205. The other role played by lens system 731 is to collect the radiation reflected from sample 205 back into

polarization-maintaining fiber **372**. Quarter wave plate **733** is oriented so that its optical axis make a 45 degrees angle with the polarization direction of the transmitted light. Reflected light from the sample propagates through **733** once again to become polarized in a direction perpendicular to mode **001**, i.e. mode **002**. Quarter wave plate **733** can be replaced by a Faraday rotator.

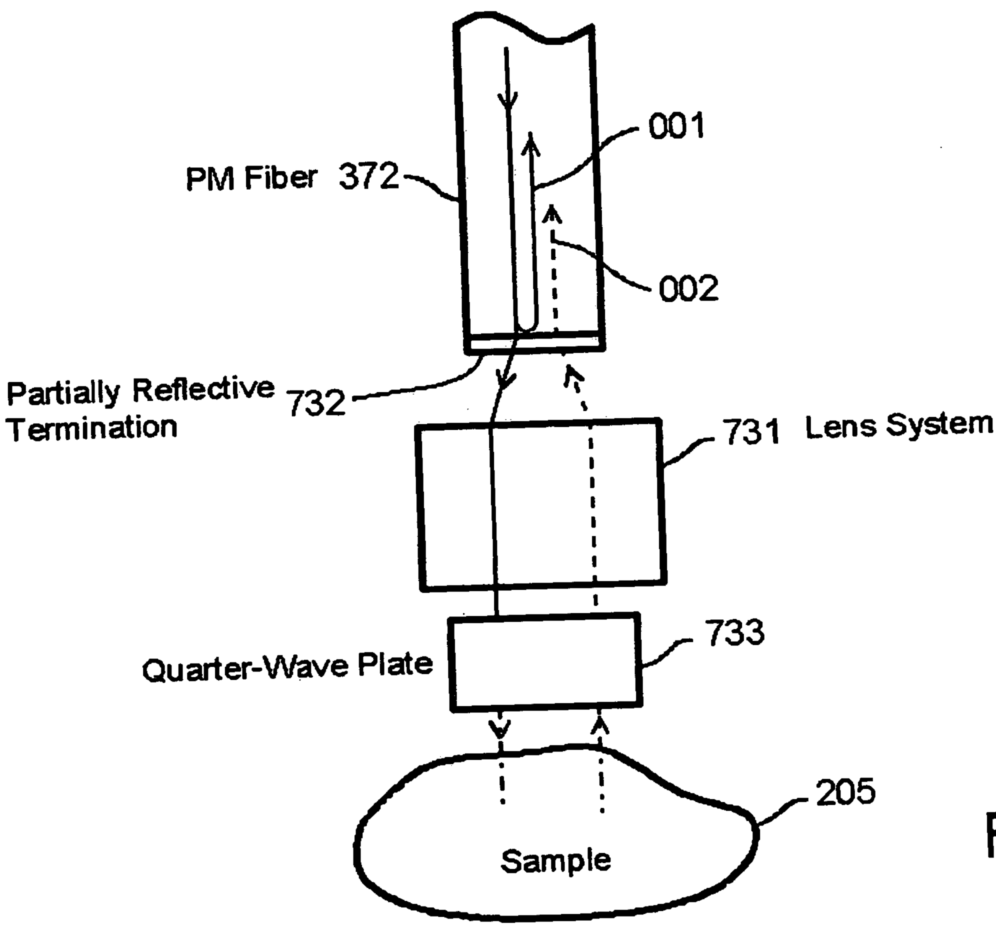


Fig. 7

[0028] Because there is only one polarization mode enters polarization-preserving circulator **610** from waveguide **371**, circulator **610** can be constructed with more common optical components as shown in Fig. 8. Polarization-maintaining circulator **811** is used to convey only one polarization mode among its three ports, rather than both modes as in the case shown in Fig. 3. Two additional polarizing beam splitter **812** and **813** are coupled to polarization-maintaining **811** so that both polarization modes entering Port 2 are conveyed to Port 3 and remain independent.

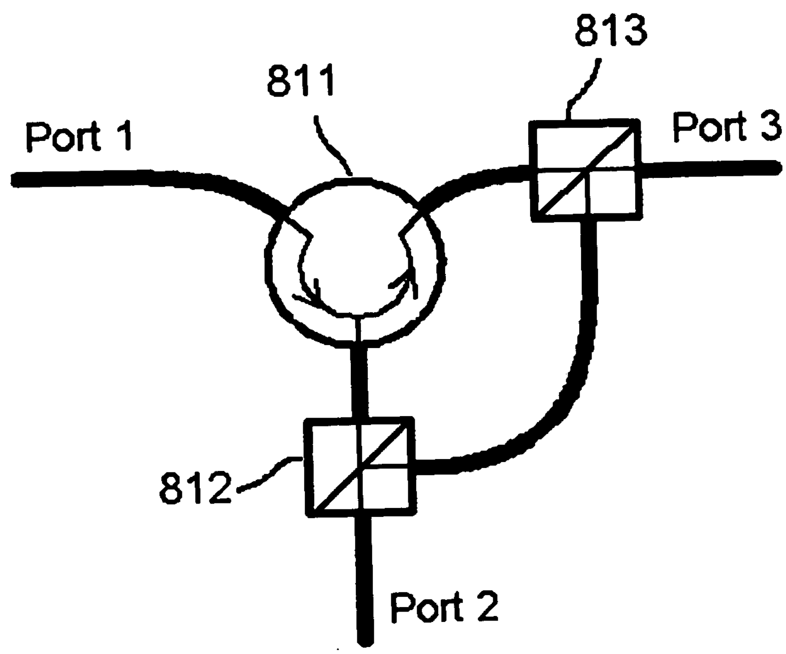


Fig. 8

[0029] In cases it is beneficial to obtain information about certain substances, identifiable through their spectral absorbance, dispersed in the samples. For this purpose a tunable bandpass filter is added to the systems, as shown in Fig. 2 and Fig. 5. The role of the tunable bandpass filter is to allow a variable portion of the source spectrum to pass while measuring the distribution of the complex reflection coefficient with the method described previously.

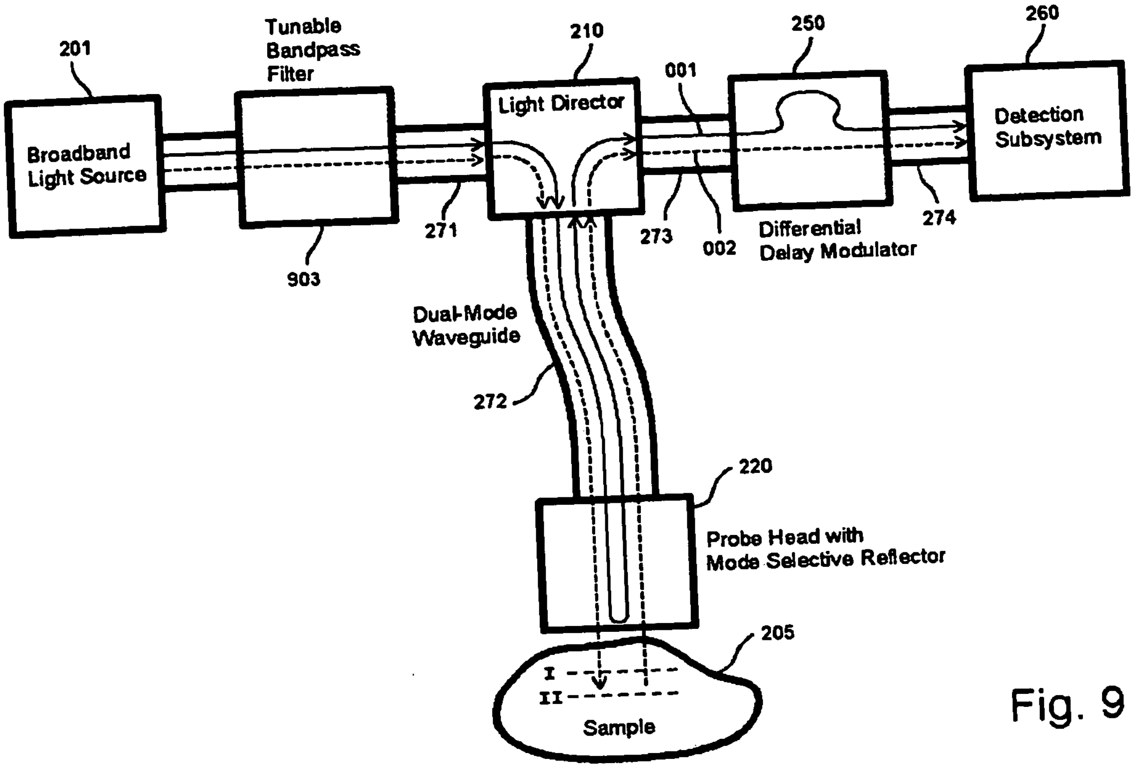


Fig. 9

[0030] Referring to Fig. 9, let us assume that we would like to acquire the absorption characteristics of a layer bounded by interfaces I and II. For the simplicity of description let us assume that the spectral absorption of the substance in the layer is characterized by a wavelength dependent attenuation coefficient $\mu_h(\lambda)$ and that of other volume is characterized by $\mu_g(\lambda)$. Let us further assume that the substance in the vicinity of interface I (II) possesses an effective and wavelength independent reflection coefficient r_I (r_{II}). If the characteristic absorption of interest is covered by the spectrum

of the light source we can use a filter with bass band tunable across the characteristic absorption as shown in Fig. 11. First, one should adjust differential delay modulator **250** so that the path length traveled by mode **001** matches that of radiation reflected from interface I in mode **002**. At this point one can scan the pass band of filter **903** while recording the oscillation of the measured signal due to a periodic differential phase generated by **250**. The oscillation amplitude as a function of wavelength is given by

[0031] $$A_I(\lambda)=r_I e^{-2\mu_g(\lambda)z_I} \quad (6)$$

where z_I is the distance of interface I measured from the top surface of the sample. Now if we readjust differential delay modulator **250** so that the path length traveled by mode **001** matches that of radiation reflected from interface II in mode **002** and repeat the measurements, we get

[0032] $$A_{II}(\lambda)=r_{II} e^{-2\mu_g(\lambda)z_I-2\mu_h(\lambda)z_{II}}, \quad (7)$$

where z_{II} is the distance of interface II measured from interface I. To acquire the absorption characteristics of the layer of interest one can divide Eq. (7) by Eq. (6) to obtain

[0033] $$\frac{A_{II}(\lambda)}{A_I(\lambda)}=\frac{r_{II}}{r_I}e^{-2\mu_h(\lambda)z_{II}} \quad . \qquad (8)$$

We have thus acquired, with Eq. (8), the absorption characteristics of the layer of interest only.

[0034] It should be noted that the pass band of the filter should be narrow enough to resolve the absorption characteristics of interest and at the meantime broad enough to differentiate the layer of interest. Let us take an example to see whether this is reasonable and practical.

[0035] It is known that some predominant glucose absorption peaks in blood reside in a wavelength range between 1 and 2.5 microns. The width of these peaks are approximately 150 nm. To resolve the peaks we can choose the bandwidth of the tunable bandpass filter to be around 30 nm. The depth resolution is determined by the following equation:

$$\frac{2\ln(2)}{\pi}\frac{\lambda_o^2}{\Delta\lambda}=60\mu m \qquad (9)$$

Therefore, using the system depicted in Fig. 9 one can determine the absorption characteristics of the glucose in tissue layers no less than 60 μm thick. It is well known that human skin

consists of a superficial epidermis layer that is typically 0.1 mm thick. Underneath epidermis is the dermis, approximately 1 mm thick, where glucose concentrates in blood and interstitial fluids. The above analysis indicates that it is possible for us to use the apparatus shown in Fig. 9 to isolate the absorption characteristics of the dermis from that of the epidermis and other layers.

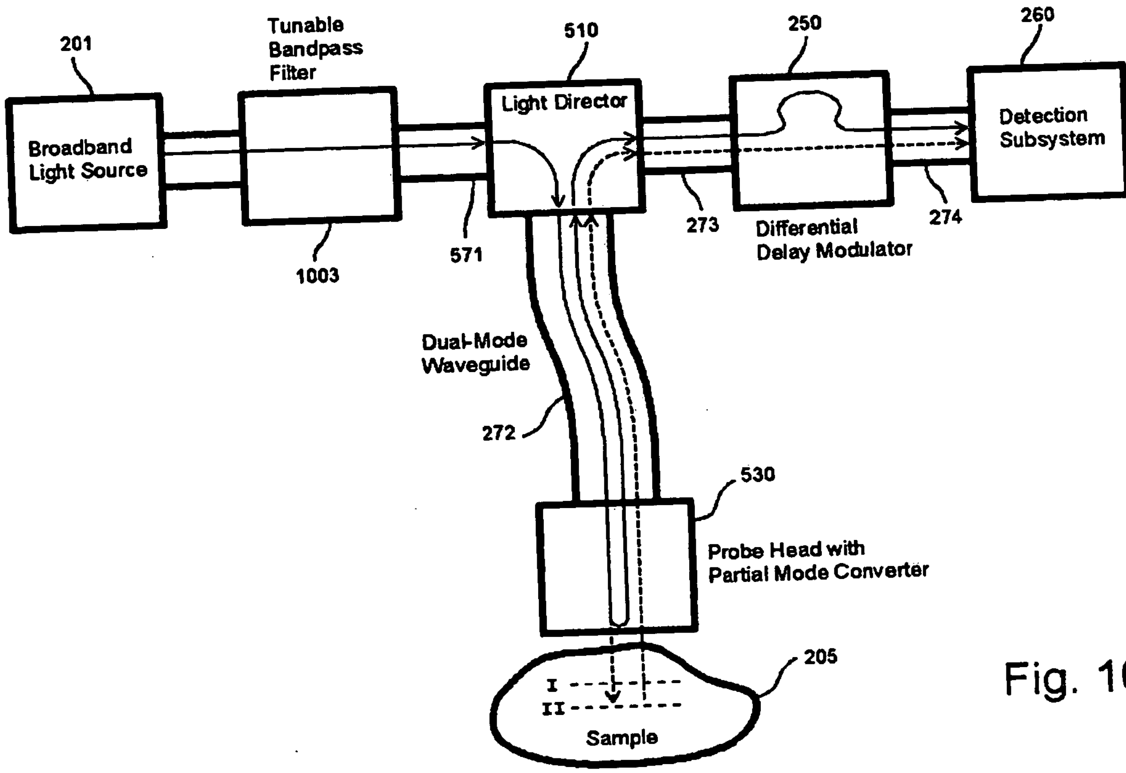


Fig. 10

[0036] It is clear from Eq. (9) that the product of spectral resolution and layer resolution is a constant for a given center

wavelength λ_0. The choice of the filter bandwidth should be made based on the tradeoff between these two resolutions against the specific requirements of the measurement.

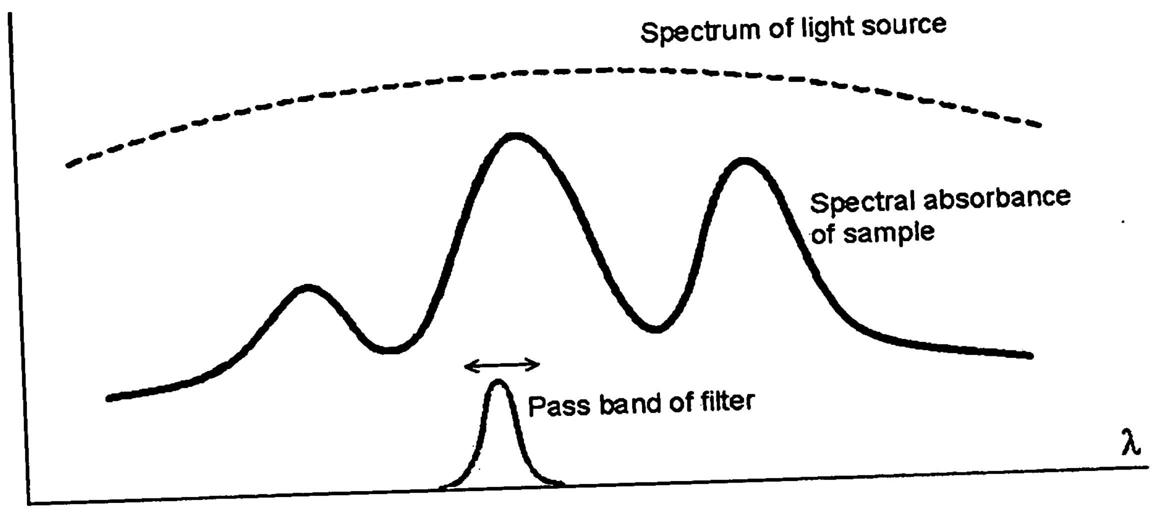


Fig. 11

[0037] A tunable bandpass filter can also be added to the optical system depicted in Fig. 5, as shown in Fig. 10. It can be operated the sample way as described above to acquire the absorption characteristics of an isolated volume inside a sample. Fig. 11 illustrates the operation of the tunable bandpass filter which selects a narrow spectral band within the spectrum of the light source to measure the spectral feature of the sample.

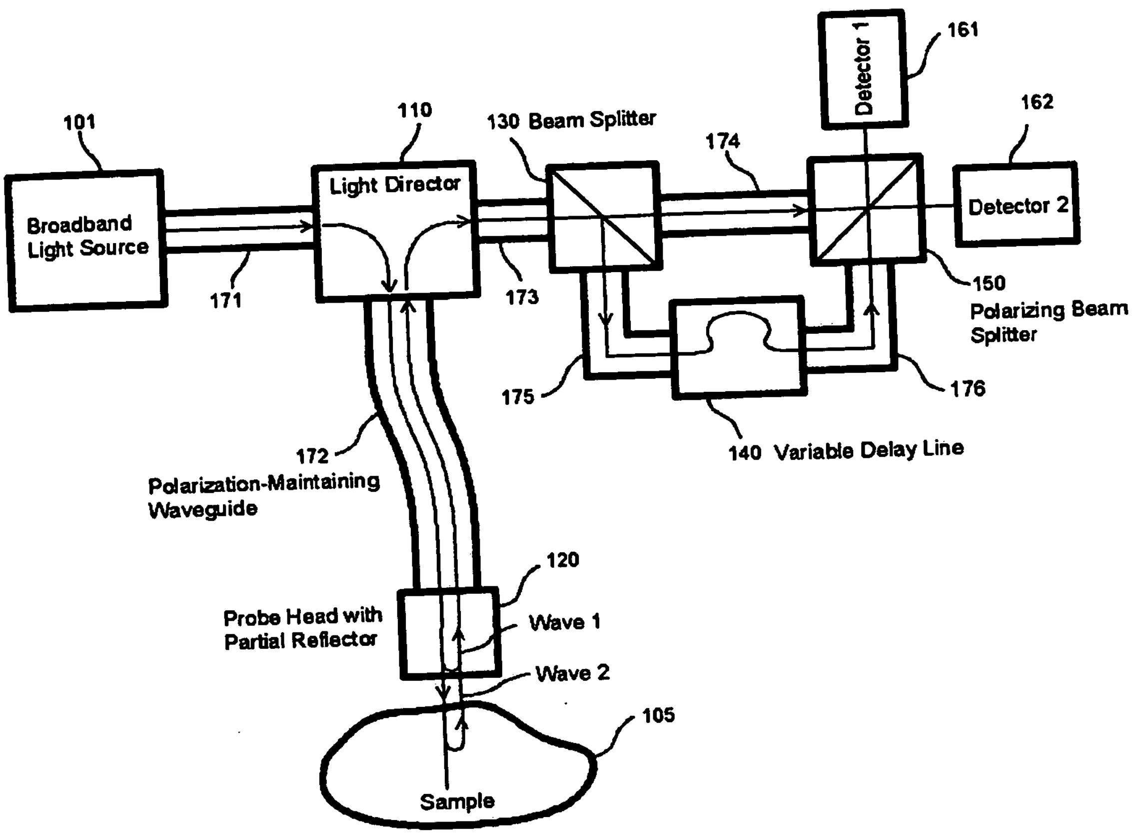


FIG. 12

[0038] FIG. 12 further shows a system for acquiring information of optical inhomogeneity and other properties in substances with only one propagation mode inside waveguides. In the design depicted by Fig. 12, broadband or low-coherence light from Broadband Light Source 101 is directed to Probe Head 120 by means of polarization-

maintaining waveguides 171 and 172. A partial reflector in the Probe Head reverses the direction of a small portion of the light, creating Radiation 1, while transmitting the remainder to Sample 105. Backscattered or reflected light, or Radiation 2, from Sample is collected by Probe Head and traveling towards Light Director 110 which conveys the light to Beam Splitter 130.

[0039] Beam Splitter 130 splits the light into two parts, one propagating towards Polarization Beam Splitter 150 directly while the other propagating through Variable Delay Line 140 before reaching 150. Polarization Beam Splitter 150 splits the combined light into two parts, orthogonal in polarization to one another, that are received by two photo detectors, 161 and 162.

[0040] Different from the previous examples, the light reflected from Partial Reflector in Probe Head 120, Radiation 1, has the same polarization as the light collected from the sample, Radiation 2. Therefore both Radiation 1 and 2 travel in the same propagation mode in the waveguides, 172 and 173. Each of the optical radiation is split into two parts by 130. As Radiation 1 and 2 are reflected from different locations they experience different optical path lengths when reaching Beam Splitter 130. The effect of Variable Delay Line 140 is to add an adjustable amount of delay, relative to the other split light in Waveguide 174.

[0041] Variable Delay Line 140 can be adjusted so that the partial Radiation 1 reaching Polarization Beam Splitter 150 from waveguide 176 can be made to experience a similar optical path length as the partial Radiation 2 reaching 150 from waveguide 174. Their superposition at the photo detectors causes measurable intensity variation as their relative path length is being varied by 140. This variation can be utilized to retrieve information regarding sample inhomogeneity and other properties.

[0042] An implementation of the system using polarization maintaining optical fibers is shown in Fig. 13. Optical radiation reflected from Partial Reflector 222 and from Sample 205 travel in Polarization-Maintaining (PM) Fiber 272 in the same mode. The main portions of Radiation 1 and 2 are deflected to Mirror 1 while the remaining portions are directed to Mirror 2 by Beam Splitter 230.

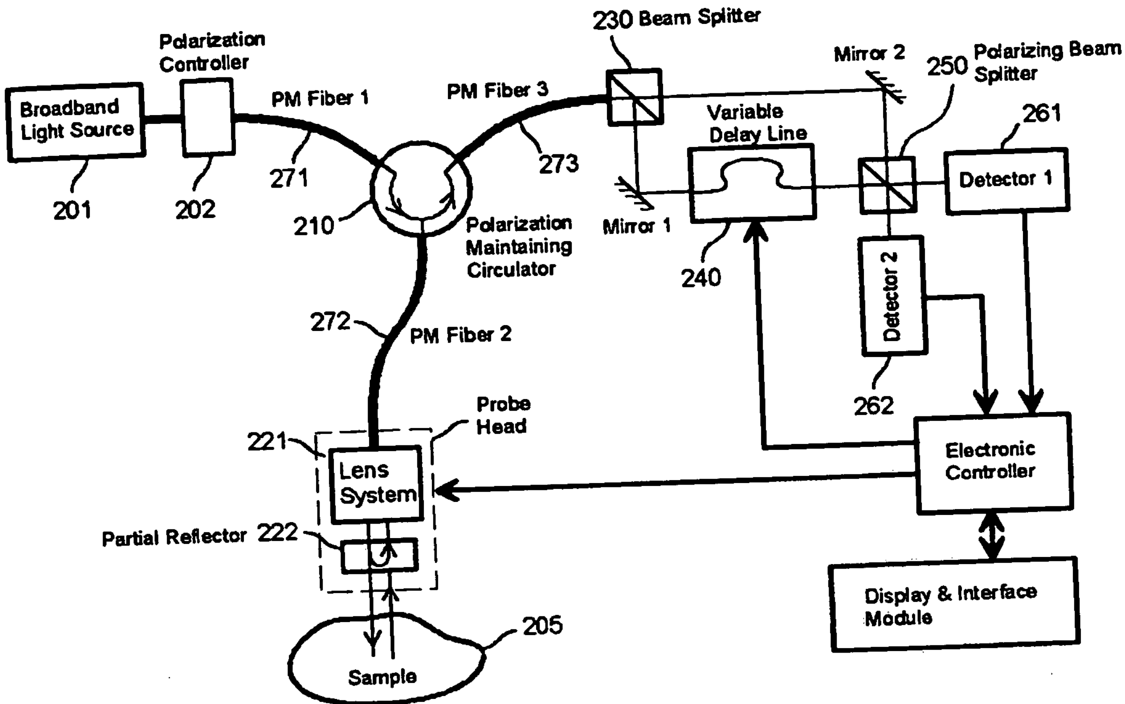


FIG. 13

[0043] The incident plane of Polarizing Beam Splitter 250 can be made to have an finite angle with respect to the polarization directions of light from both Mirror 2 and Variable Delay Line 240. That way, light energies received by both detectors are superposition of the two radiations, i.e., Radiation 1 and Radiation 2. It should be appreciated that the linkage between 230 and 250 can be made by means of optical fibers, eliminating the two mirrors.

[0044] In FIGS. 12 and 13, the spacing between the optical head and the sample may be greater than the sample depth of interest so that, upon reaching 250, the partial Radiation 1 experiences optical path length similar only to that of partial Radiation 2. In other words, split parts of the same radiation do not experience similar optical path length during the operation of the system.

[0045] A possible optical arrangement for the Probe Head is shown in Fig. 14. The partial reflector can be realized with a partially reflective fiber termination. An uncoated fiber tip has a reflectivity of approximately 4%. Optical coating can be used to change the reflectivity to a desirable value.

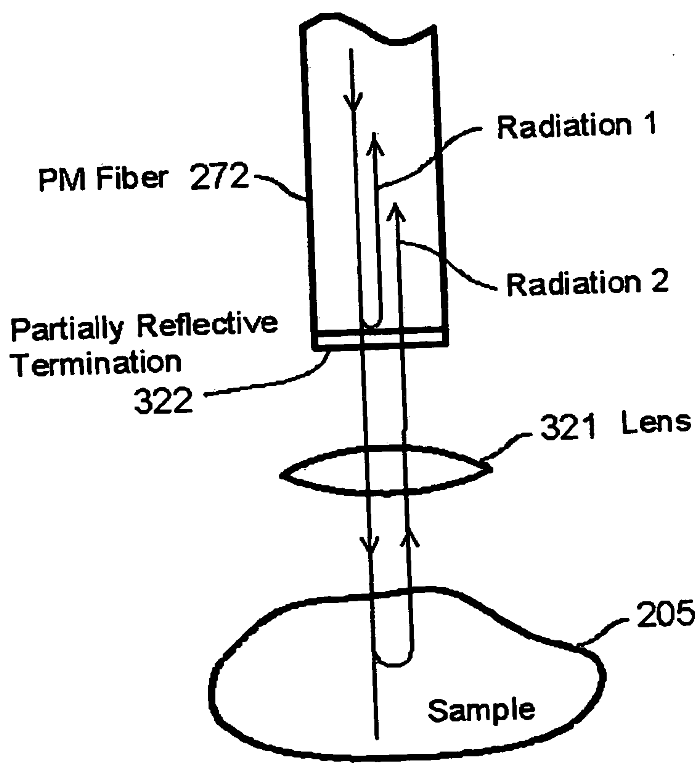


FIG. 14

[0046] The reflectance of the fiber termination should be chosen based on several factors. In one respect, Radiation 1 should be strong enough so that its superposition with Radiation 2 creates adequate intensity variation. On the other hand, Radiation 1 should not be too strong as it may overwhelm the photodetectors, prohibiting the used of high gain in the detection systems. For optimized operation of the system, one may want to choose the reflectance of the fiber termination to be comparable to the total light collected by the fiber from the sample.

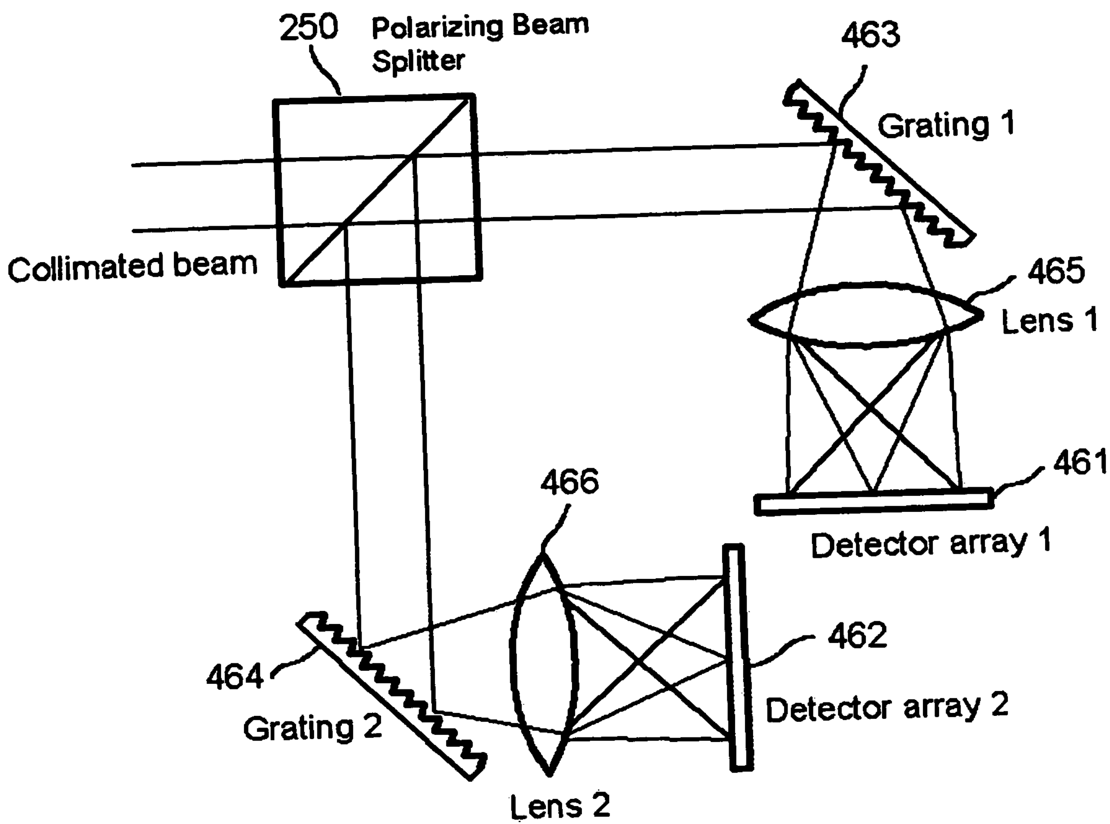


FIG. 15

[0047] In order to resolve the spectral information from the sample a detection system with gratings and detector arrays can be used, as shown in Fig. 15. In this arrangement, Grating 1 and Grating 2 disperse the light by wavelength. Each detector elements in Detector Array 1 and Detector Array 2 receives light in a small wavelength interval. By summing up photocurrent from all elements in an array one gets a signal equivalent to a single detector as shown in Fig. 13. By selectively measuring the photocurrent from individual or a group of elements in an

array one can acquire spectral information of the sample, in a similar way as using a bandpass filter in the previous disclosure

[0048] In all the above-mentioned examples for optical designs and implementations, there is a common and important feature, i.e. both the sample light and reference light, in the form of two independent modes, travel in the same waveguides except for the extra distance traveled by the probing light between the probe head and the sample. This feature stabilizes the relative phase, or differential optical path, between the sample light and the reference light, even in the presence of mechanical movement of the waveguides. This is in contrast to conventional interferometers in which sample light and reference light travel in different optical paths, prone to noise caused by the variation in the differential optical path. The stability of the differential optical path, achieved in the invented system, is beneficial for some phase-sensitive measurement, such as the determination of the absolute reflection phase and birefringence.

[0049] In each system described here, a lateral scanning mechanism may be implemented to change the relative lateral position of the optical head and the sample to obtain a 2-dimensional map of the sample. A xy-scanner, for example, may be engaged either to the optical head or to a sample holder that

holds the sample to effectuate this scanning in response to a position control signal.

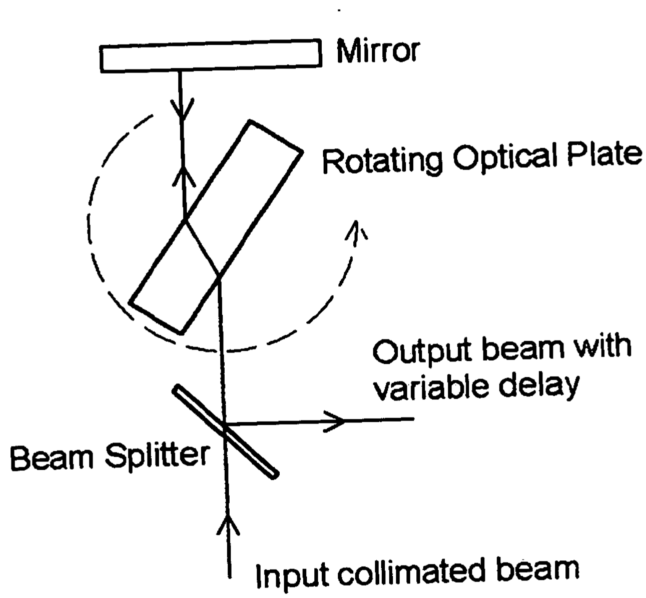


FIG. 16A

[0050] This application further describes variable optical delay devices illustrated in FIGS. 16A and 16B. Such a device may be used to change the optical path length of a light beam at high speeds. Such devices have various application. For example, fast change of optical path length is desirable in various optical instruments such as interferometers. In addition, the optical systems in this application may use such a delay device.

[0051] In the device shown in FIG. 16A, the input light beam impinges on and transmits through the rotating Optical Plate.

The Mirror placed on the opposite side of the Optical Plate is perpendicular to the light beam. The reflected light beam traces the same optical path back traveling until it encounters the Beam Splitter. The Beam Splitter deflects part of the back traveling light to a different direction as the output beam.

[0052] The variation of the optical path length is caused by the rotation of the Optical Plate. The Optical Plate should be made of good quality optical material. The two optical surfaces should be flat and well polished to minimize distortion to the light beam. In addition, the two surfaces should be parallel to one another so that the light propagation directions on both sides of the Optical Plate are parallel. The thickness of the Optical Plate should be chosen according to the desirable delay variation and range of rotation angle.

[0053] The optical path length experienced by the light beam is determined by the rotation angle of Optical Plate. When the surfaces of the Optical Plate is perpendicular to the light beam (incident angle is zero), the path length is at its minimum. The path length increases as the incident angle increases.

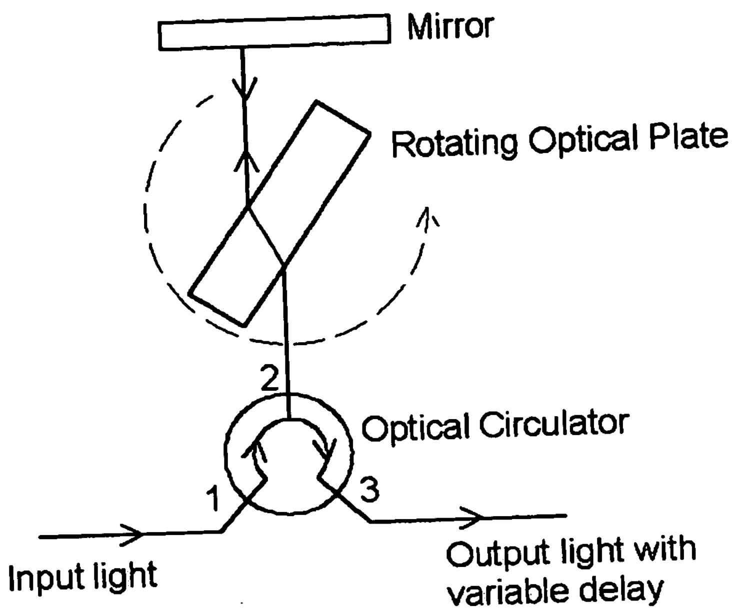
[0054] It may be beneficial to collimate the input light beam so that it can travel the entire optical path without significant divergence. The Optical Plate can be mounted on a motor for periodic variation of optical delay. Good quality

mirror with flat surface should be used. The Mirror should maintain its perpendicular orientation to the light beam.

[0055] If a linearly polarized light is use, it is beneficial to have the polarization direction of the light parallel to the incident plane (in the plane of the paper) as less reflection occurs at the surfaces of Optical Plate for this polarization compared to other polarization directions. Antireflection coatings can be used to further reduce the light reflection on the surfaces of the Optical Plate.

[0056] Using beam splitter shown in Fig. 16A, a maximum of 25% of the total input light remains in the output light as the light beam encounters the Beam Splitter twice, losing half of the light energy each time. To overcome this drawback an optical circulator can be used in place of the beam splitter, as shown in Fig. 16B.

FIG. 16B



[0057] The Optical Circulator shown in Fig. 2 is such a device that nearly all light entering Port 1 exits from Port 2 while nearly all light entering Port 2 exits from Port three. The optical loss of this alternative configuration is nominally zero. Commercially available optical circulators, either free-space or fiber-based, can be used for the purpose.

[0058] Additional features and implementations are further described in the Attachments I and II below.

Attachment I

The invented method and apparatus are for the purpose of acquiring, by means of a nondestructive process, images which reveal optical inhomogeneity in a volume of substances.

The invented apparatus embodies the physical principle of range detection by means of the interference of low-coherence light and optical phase detection by means of a phase modulation scheme. A possible implementation of the system is shown in Fig. 1.

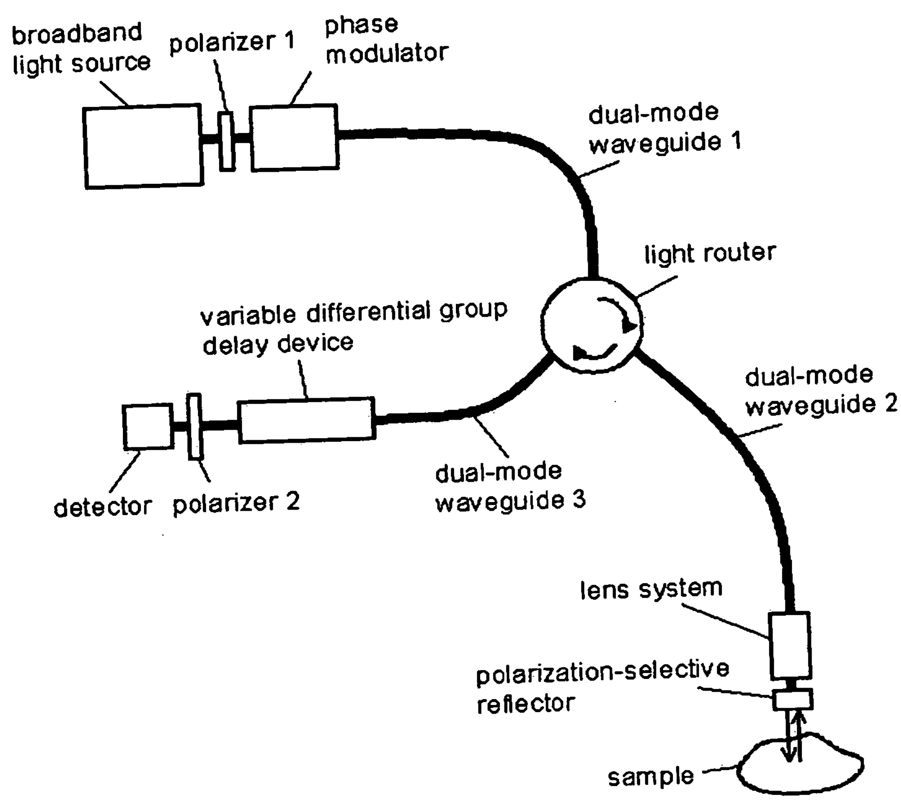


Figure 1

Light radiation from the Broadband Light Source (Source) is transmitted through Polarizer 1 that is oriented to allow the light to form both of the guided propagation modes in Dual-mode Waveguide 1 (Waveguide 1). The Optical Phase Modulator (Modulator) is employed to modulate the optical phase of light in one guided mode relative to the other. The Light Router (Router) directs light waves from Waveguide 1 to Dual-mode Waveguide 2

(Waveguide 2). At the end of Waveguide 2, the Lens System collimates or focuses the light beams. One of the two guided waves is reflected back to Waveguide 2 by the Polarization-selective Reflector (PSR) while the other mode is transmitted to impinge on the sample. Back reflected or scattered the light from the sample is collected by the Lens System to propagate towards the Router along with the light reflected by PSR. The Router directs the light waves traveling towards it in Waveguide 2 to Dual-mode Waveguide 3 (Waveguide 3). A Variable Differential Group Delay (VDGD) device is inserted in or connected to Waveguide 3. The function of the VDGD is to introduce a controllable amount of optical path difference between the two waves. Placed in front of the Detector, Polarizer 2 projects both of the guided waves onto the same polarization direction so that the changes in optical path difference and the optical phase difference between the two propagation modes cause intensity variations, detectable by the Detector.

The spectrum of the Source must be broad enough in order for the system to have sufficient ranging resolution. Some semiconductor light emitting diodes (LED) and amplified spontaneous emission (ASE) sources possess the appropriate spectral properties for the purpose. The Modulator must be the variable waveplate type. In other words, the modulator should vary the optical phase in one guided wave with respect to the other. Electro-optic materials such as $LiNbO_3$ crystal and PLZT ceramic can be used to construct this kind of modulators. The dual-mode waveguides (Waveguide 1 to 3) must be able to support two distinctive propagation modes which are mutually orthogonal to one another. One kind of practical and commercially available waveguide is the polarization maintaining optical fiber. A polarization maintaining fiber can carry two propagation modes, namely, the s-wave polarized along its slow axis and the p-wave polarized along its fast axis. In good quality polarization maintaining fibers these two modes have virtually no energy exchange, or coupling. The Router directs the flow of optical waves according to the following scheme: incoming light waves from Waveguide 1 are routed to Waveguide 2; incoming light waves from Waveguide 2 are routed to Waveguide 3. The Router is ideally required to maintain the separation of the guided modes. For instance, the s-wave in Waveguide 1 should be routed to Waveguide 2 as s-wave or p-wave only. In practice, one can use

a polarization-maintaining circulator in which there is minimal mode coupling. The lens system is used to concentrate the light energy into a small area, facilitating spatially resolved studies of the sample in a lateral direction. The Polarization-selective Reflector (PSR) is to reverse the propagation direction of one of the two waves in Waveguide 2 as it reaches the end of the waveguide while transmitting the orthogonal wave. The PSR may consists of a polarization sensitive beam splitter and a mirror as shown in Fig. 2. In the assembly the polarizing beam splitter reflects one of the two waves, s-wave shown, while transmitting the other. The mirror, that can be directly coated on the beam splitter, reflects the light that subsequently bounces from the splitter the second time before re-entering the waveguide through the Lens System.

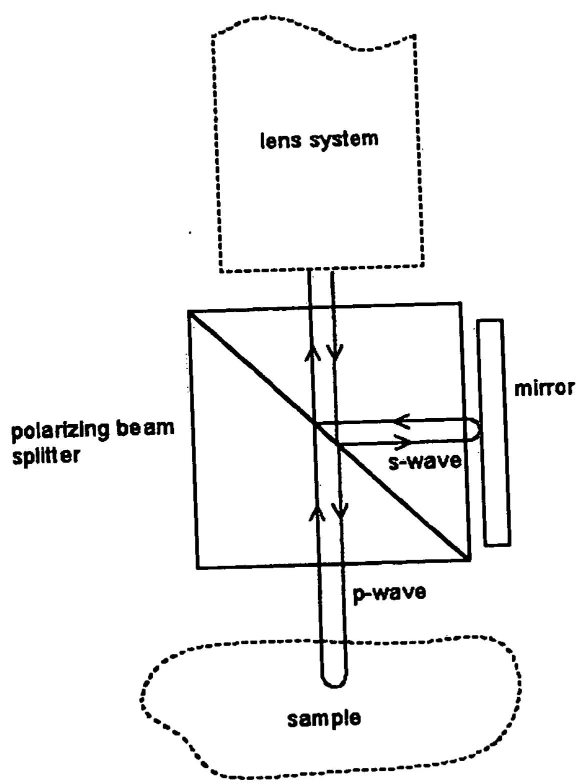


Figure 2

A number of hardware choices are available for the VDGD device. For instance, an assembly of a polarizing beam splitter(s) and a movable collimator or mirror, that provides the adjustable path length for one of the two waves, can be used. Another possible choice is a piezoelectric stretcher of polarization maintaining fibers.

Using the above-mentioned optical system to acquire images of optical inhomogeneity in samples data acquisition and control electronics must be added. A design diagram for such a system is shown in Fig. 3.

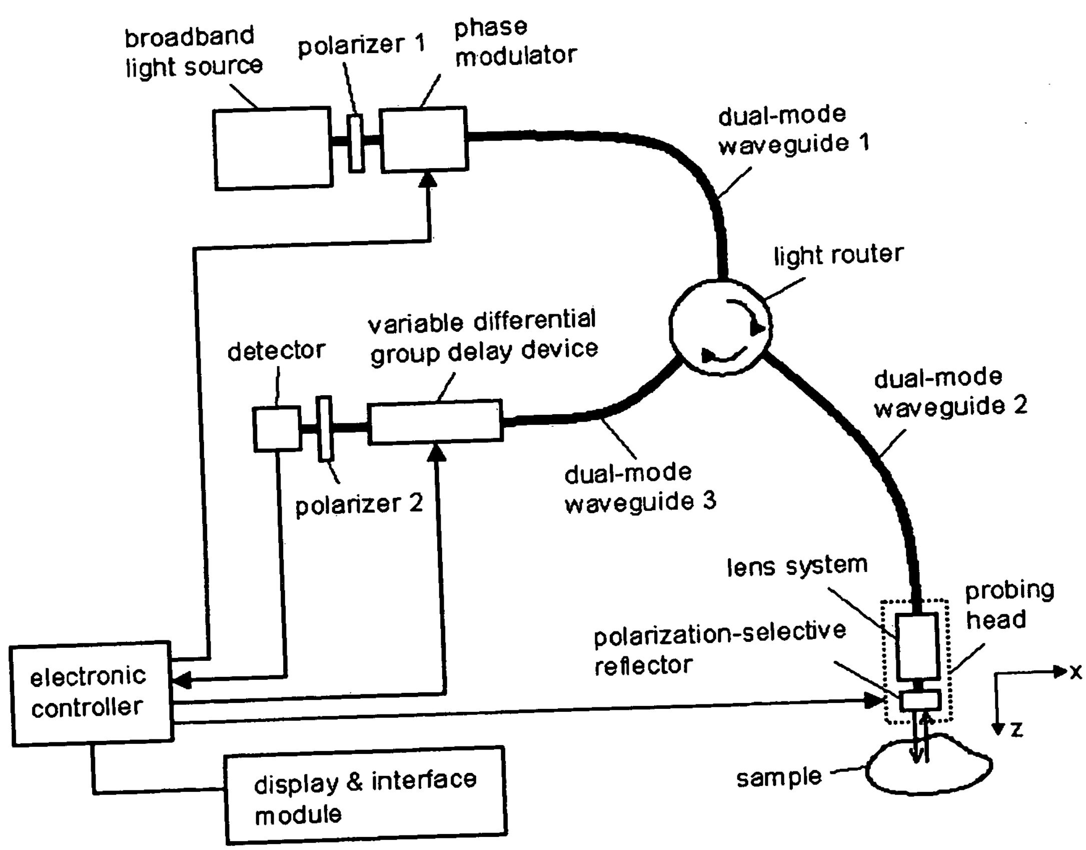


Figure 3

The electronic controller, according to the instructions from the human interface, executes an appropriate program that includes delivering driving signals to Modulator, VDGD and the moving mechanisms of Probing Head, taking and storing photo-electric signal from the detector, processing the stored information, sending signals and data to be displayed on Display Module. A preferred mode of operation is described below.

The light from the Source is typically partially polarized. It is preferable to align Polarizer 1 so that maximum amount of light is transmitted and that the transmitted light is coupled to both of the guided modes in Waveguide 1 with the same amplitude. If we designate the electric field transmitting the polarizer E, the electric fields in Waveguide 1 in the two guided modes can be expressed as:

$$\begin{cases} E_s = \dfrac{1}{\sqrt{2}} E, \\ E_p = \dfrac{1}{\sqrt{2}} E. \end{cases} \tag{1}$$

It should be appreciated that the light has a finite spectral width (broadband or partially coherent). The fields can be described by the following Fourier integral:

$$E = \int E_\omega e^{j\omega t} d\omega \ . \tag{2}$$

For the simplicity of the analysis, let us first consider a thin slice of the spectrum, i.e. a lightwave of a specific wavelength. Without loosing generality we can assume all the components, including polarizers, waveguides, Router, PSR and VDGD, are lossless. Let us designate the reflection coefficient of the sample r, that is complex in nature. The p-wave picks up an optical phase, Γ, relative to the s-wave as they reach Polarizer 2:

$$\begin{cases} E_s = \frac{1}{\sqrt{2}} E, \\ E_p = \frac{1}{\sqrt{2}} r E\, e^{j\Gamma}. \end{cases} \tag{3}$$

The light that passes through Polarizer 2 can be expressed by

$$E_a = \frac{1}{\sqrt{2}}(E_s + E_p) = \frac{1}{2} E\left(1 + r e^{j\Gamma}\right). \tag{4}$$

The intensity of the light that impinges on the photo-detector is given by:

$$I = E_a E_a^* = \frac{1}{4}|E|^2\left[1 + |r|^2 + 2|r|\cos(\Gamma + \delta)\right]. \tag{5}$$

where phase angle δ reflects the complex nature of the reflection coefficient of the sample and is defined by

$$r = |r| e^{j\delta}. \tag{6}$$

Now if we let Modulator to exert a sinusoidal phase modulation, with magnitude M and frequency Ω, in the p-wave with respect to the s-wave, we can rewrite the light intensity as follows:

$$I = \frac{1 + |r|^2}{4}|E|^2 + \frac{|r|}{2}|E|^2 \cos[M \sin(\Omega t) + \varphi + \delta] \quad . \tag{7}$$

where phase angle φ is the accumulated phase slip between the two modes, not including the periodic modulation due to Modulator. We can adjust the system, by means of the VDGD or the static phase shift in Modulator, to eliminate φ. The waveform of I is graphically shown in Fig. 4.

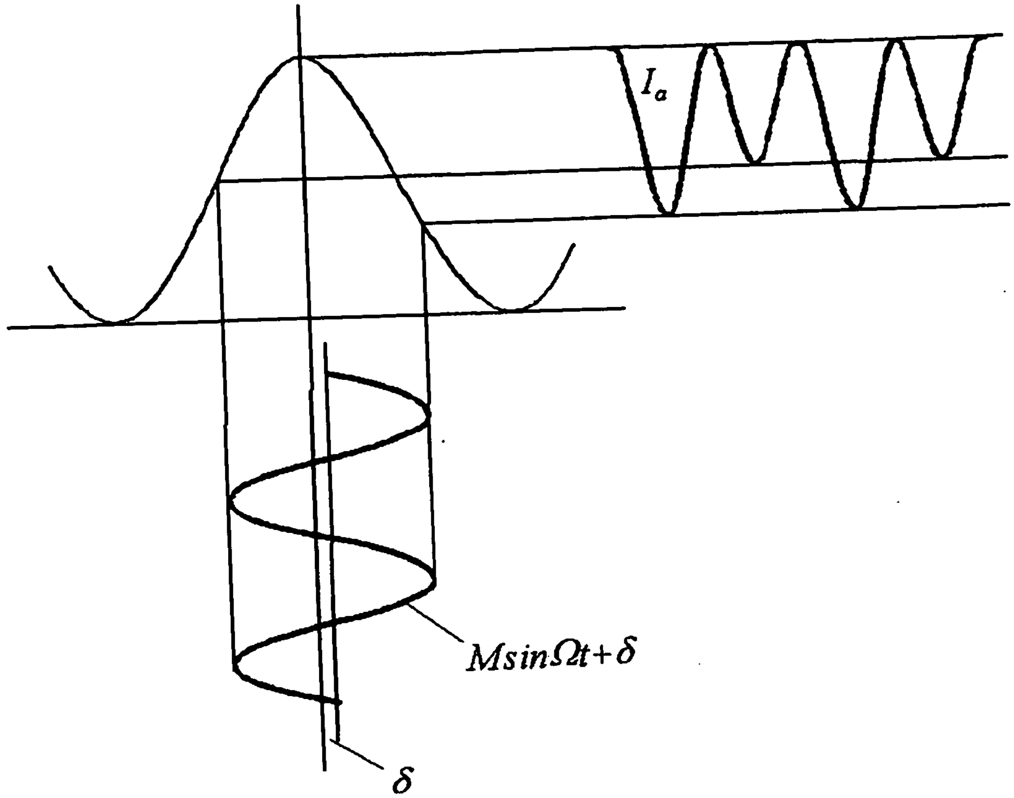


Figure 4

From the figure we can see that the detected light intensity exhibits an oscillating waveform that possesses a base frequency of Ω and its harmonics. The amplitudes of the base frequency and each of the harmonics are related to δ and $|r|$. It is straightforward to derive the mathematical expressions for the relationships between r and the harmonics. For instance, the amplitude of the base-frequency oscillation and the second harmonic are found to be:

$$A_\Omega = 0.5|E|^2 J_1(M)|r|\sin\delta \; ; \tag{8a}$$

$$A_{2\Omega} = 0.5|E|^2 J_2(M)|r|\cos\delta \; , \tag{8b}$$

where J_1 and J_2 are Bessel functions of the first and second order, respectively. From Eq. (8a) and (8b) one can solve for $|r|$ and δ, i.e. the complete characterization of r. We can

therefore completely characterize the complex reflection coefficient r by analyzing the harmonic content of various orders in the intensity waveform I. In particular, the presence of the base-frequency component in I is due to a finite δ.

Now let us examine the consequence of having a broadband light source. When there is a significant differential group delay between the two propagation modes there must be an associated large phase slippage φ that is wavelength dependent. A substantial wavelength spread in the light source means that the phase slippage also possesses a substantial spread. Such a phase spread cannot be eliminated by a phase control device that does not also eliminate the differential group delay. In this case the detected light intensity is given by the following integral:

$$I = \int \left\{ \frac{1+|r|^2}{4} |E(\lambda)|^2 + \frac{|r|}{2} |E(\lambda)|^2 \cos[M \sin(\Omega t) + \varphi(\lambda) + \delta] \right\} d\lambda \,. \qquad (9)$$

It is easy to see that if the range of $\varphi(\lambda)$ is comparable to π for the bandwidth of the light source no oscillation in I can be observed as oscillations for different wavelengths cancel out because of their phase difference. This phenomenon is in close analogy to the interference of white light wherein color fringes are visible only when the path difference is small (the film is thin).

The above analysis demonstrates that the use of a broadband light source enables range detection using the proposed apparatus. In order to do so, we must let the s-wave to have a longer optical path in the system compared to the p-wave (not including its round-trip between Probing Head and Sample). For any given path length difference in the system there must be a matching distance between Probing Head and Sample, z, that cancels out the path length difference. If an oscillation in I is observed the p-wave must be reflected from this specific distance z. By varying the path length difference in the system and record the

oscillation waveforms we can therefore acquire the reflection coefficient r as a function of the longitudinal distance z, or depth. By moving Probing Head laterally, we can also record the variation of r in the lateral directions.

In summary, the described system can be used to acquire information regarding the optical inhomogeneity in a substance by measuring the oscillations in the detected light as a function of the lateral and longitudinal directions. The waveforms can then be used to construct the spatially resolved complex reflection coefficient of the substance under study.

The operation of the described system for acquiring images of optical inhomogeneity should include routines such as the one shown below:

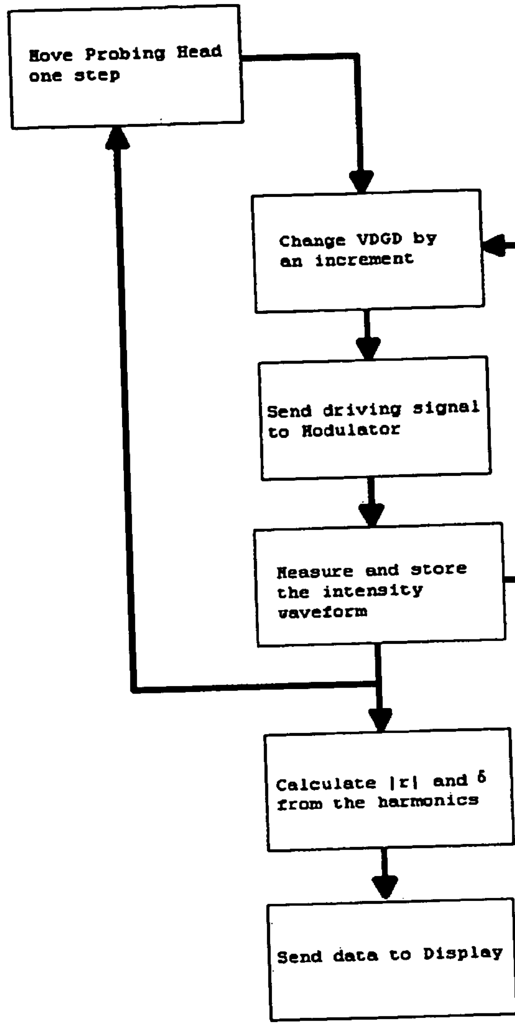


Figure 5

The above shown operation sequence allows us to display and store images of $|r|$ and δ as functions of the lateral and longitudinal directions. The data can be further used to determine the spatial distribution of the refractive index and the absorption coefficient of the substance under study. Images of this kind should be of value to biomedical field for tissue examination and to the study of other layered structures such as oil paintings.

Other Embodiments

Alternative to the optical design shown in Figure 1, there are other possible embodiments of the invention. One such embodiment is shown in Figure 6. In this design, the probing light is delivered to the sample through one dual-mode waveguide and the reflected/scattered light is collected by another dual-mode waveguide. Shown in the figure, Waveguide 1 delivers the light waves to the fiber tip. One of the two modes is reflected into Waveguide 2 while the orthogonal component impinges on the sample. The collection of the reflected/scattered light from the sample is through Waveguide 2. With this probing head, the mirror (shown in Fig. 2) should be aligned so that the light is reflected into Waveguide 2 instead of Waveguide 1. The advantage of this design is the elimination of the optical circulator.

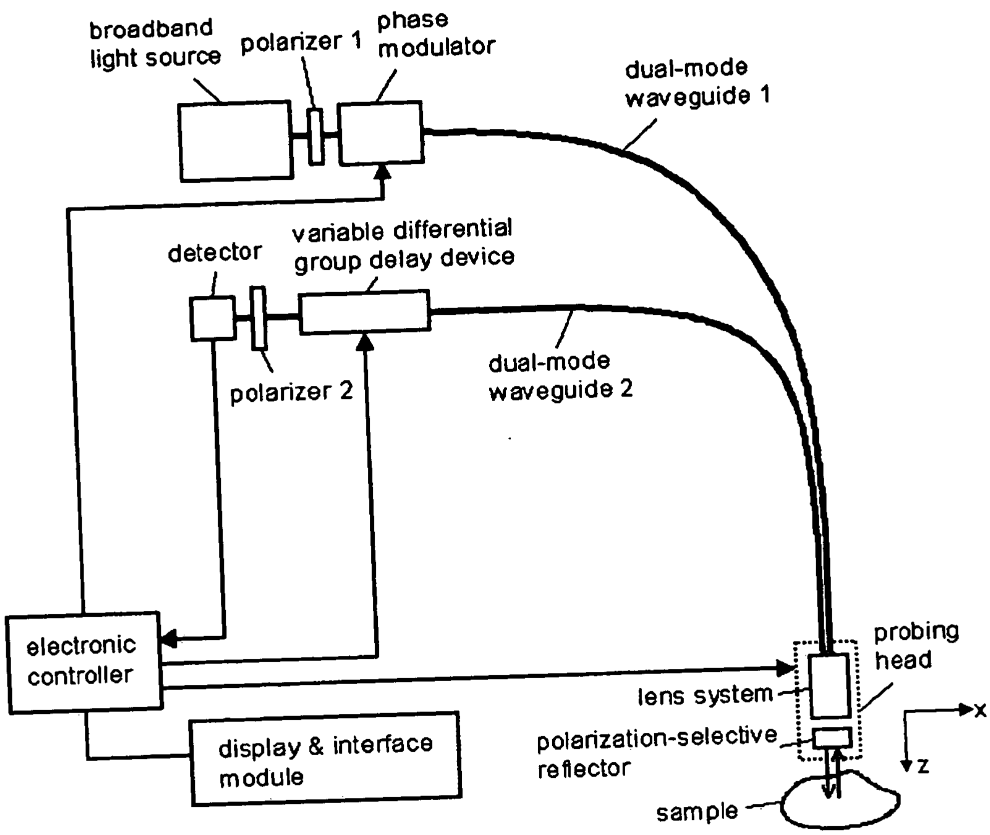


Figure 6

Yet another different embodiment of the invention is shown in Figure 7 in which the design of the probing head is different from what is shown in Figure 1. In place of the polarization-selective reflector, a polarization rotating device is utilized. Details of the probing head is shown in Figure 8.

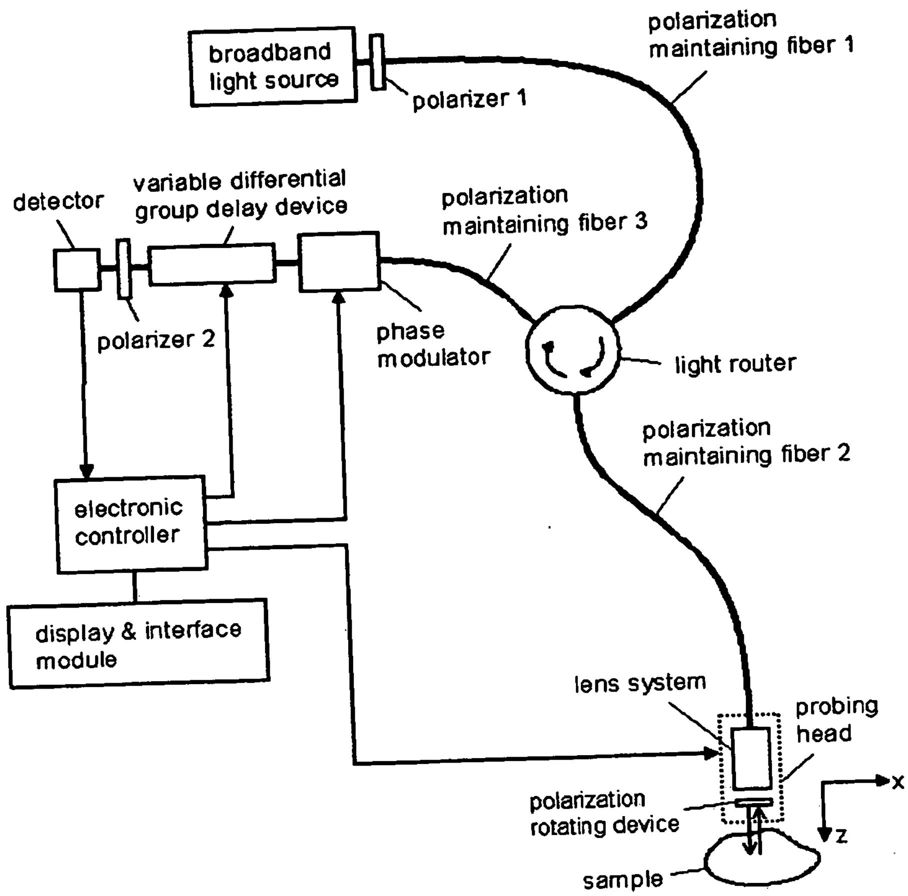


Figure 7

The effect of the polarization rotating device is to convert the state of polarization of the light returning from the sample to the orthogonally linear state. With this probing head design, the light is couple into Polarization Maintaining Fiber 1 (PM Fiber 1) in only one of the two modes, for instance, the polarization mode aligned with the slow axis of the fiber, designated as s-state. The partially reflective surface of the fiber tip causes a portion of the light to reverse its propagation direction, remaining polarized in the s-state. The other portion of the light exits the fiber and encounters the Quarter-Wave Plate. If the Quarter-Wave Plate is oriented in such a way that its optical axis makes an 45-degree angle with the p-state, the light becomes

circularly polarized as it reaches the sample. If the sample is not depolarizing or birefringent the reflected/scattered light remains circularly polarized. Before returning to the fiber, the reflected/scattered light encounters the Quarter-Wave Plate for the second time. Once again the Quarter Wave Plate alters the state of polarization of the probing light, making it linear, however, orthogonal to the s-state. Now there are two modes of light propagating in the reverse direction, i.e., light in s-state reflected by the fiber tip and light in p-state reflected from the sample.

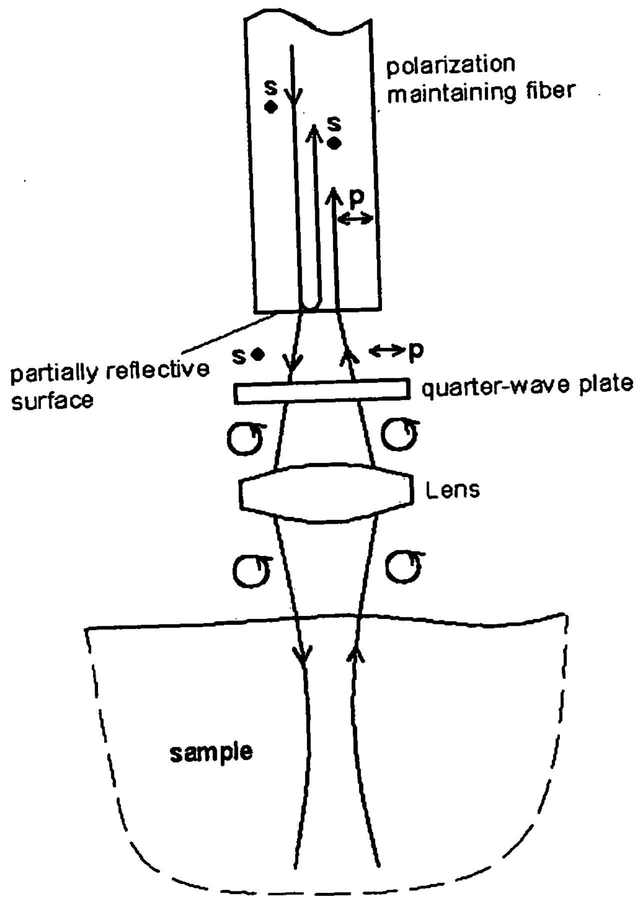


Figure 8

The light in the p-state (from the sample) lags the s-state light because of the extra travel from fiber tip to the sample and returning. As in the first embodiment, the Variable Differential Group Delay (VDGD) device is utilized to equalize the optical path of the two modes for ranging. The Modulator is relocated to Polarization Maintaining Fiber 2 (PM Fiber 2). The effect of the modulator is the same as described earlier, i.e., to create a periodic phase difference between the two modes so that intensity oscillation in a desired fashion is generated.

In all the above-mentioned embodiments there is a common and important feature - both the probing light and reference light travel in the same waveguides except for the extra distance traveled by the probing light between the probing head and the sample. This feature stabilizes the relative phase, or differential optical path, between the probing light and the reference light, even in the presence of mechanical movement of the fibers. This is in contrast to conventional fiber interferometers in which probing light and reference light travel in different branches of fiber, prone to noise caused by the variation in the differential optical path. The stability of the differential optical path, achieved in the invented system, is essential for the determination of the phase angle, δ.

Attachment II

The invention is concerned with a method and apparatus to monitor the glucose level of diabetes patients with an optical and noninvasive technique.

Presently, dependable glucose monitors rely on taking blood samples from diabetes patients. Repeated pricking of skin can cause considerable discomfort for patients. It is therefore desirable to monitor the glucose level in a noninvasive manner.

It is well known that glucose in blood possesses "signature" optical absorption peaks in a near-infrared (NIR) wavelength range. It is also appreciated the main obstacle in noninvasive monitoring of glucose is due to the fact that a probing light beam interacts, in its path, with various types of tissues and substances which possess overlapping absorption bands. Extracting the signature glucose peaks amongst all other peaks has proven difficult.

This invention addresses the difficulty through "coherence gating", a technique by which one can acquire the absorbance spectrum of a particular and designated layer beneath the skin surface. For glucose monitoring, the designated layer is preferably the dermis layer where glucose is concentrated in a network of blood vessels and interstitial fluid, as shown in Fig. 1.

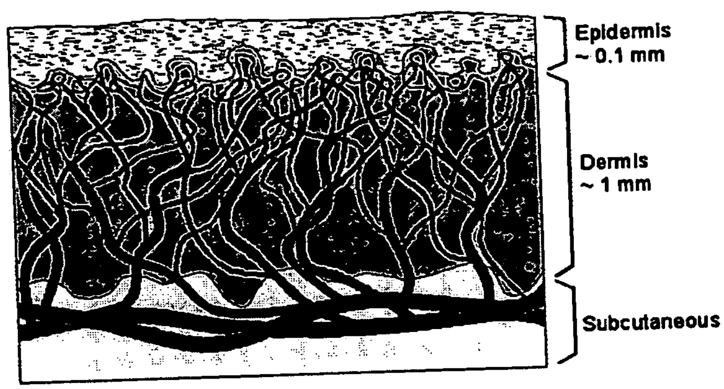


Figure. 1

The coherence gating is accomplished by the use of a low-coherence interferometer. There are many possible optical configurations for the low-coherence interferometer. Figure 2 shows one design based on a Michelson interferometer.

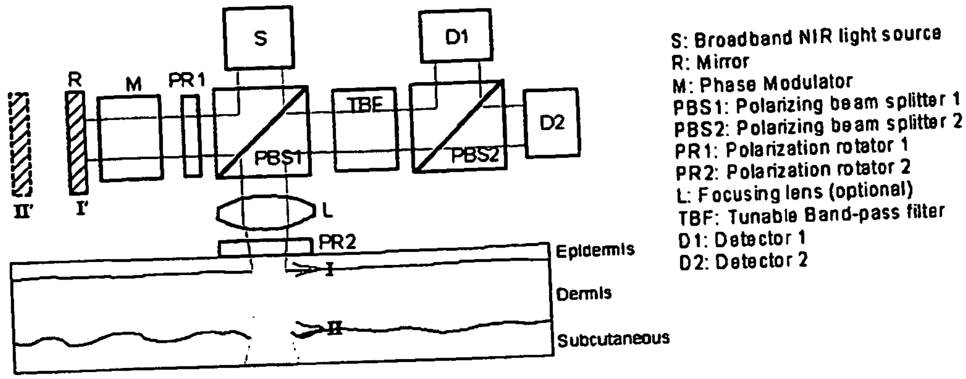


Figure 2

In the design shown, the light source emits broadband NIR radiation covering the characteristic absorption peaks of the glucose. The polarizing beam splitter, PBS1, splits the light into two parts which are mutually orthogonal in polarization to one another. While one part is directed towards a mirror, R, to be the reference beam the other is incident on the skin of a patient. The two polarization rotators, PR1 and PR2, render the polarization states of the two reflected beams orthogonal to their original states so that they are recombined at PBS1 and propagate towards the detection subsystem. The tunable bandpass filter, TBF, allows a variable portion of the spectrum in the reflected beams to reach the detectors. The movable mirror can be positioned so that its distance from PBS1 matches that between PBS1 and a desirable interface in the skin. Due to the low coherence, only the reflected (or backscattered) light originated in the vicinity of the matching interface can form interference fringes with the reference beam. Temporal interference fringes (intensity oscillation) can be generated with the help of the phase modulator.

For the simplicity of description let us assume that the wavelength dependent attenuation coefficient of the epidermis layer is $\mu_e(\lambda)$ and that of the dermis $\mu_d(\lambda)$. These attenuation coefficients are closely related to the absorbance spectra of the layers. Let us further assume that the tissue in the vicinity of interface *I* (*II*) possesses an effective reflection coefficient r_I (r_{II}). Interface *I* separates the epidermis and the dermis; and interface *II* separates the dermis and the subcutaneous tissues.

Let us first position the mirror at *I'* to approximately match interface *I*. The reflected light originated around the

interface creates an interfering echo whose amplitude is given by

$$A_I(\lambda) = r_I e^{-2\mu_e(\lambda)z_e} \tag{1}$$

where z_e is the thickness of the epidermis. Now if we relocate the mirror to II' to approximately match interface II, r_{II} gives rise to a different interfering echo whose amplitude is given by

$$A_{II}(\lambda) = r_{II} e^{-2\mu_e(\lambda)z_e - 2\mu_d(\lambda)z_d} \tag{2}$$

where z_d is the thickness of the dermis. With the use of the phase modulator these echoes interfere with the reference and produce proportional intensity oscillations measurable by the detector. To acquire the absorption characteristics of the dermis one can divide Eq. (2) by Eq. (1) to obtain

$$\frac{A_{II}(\lambda)}{A_I(\lambda)} = \frac{r_{II}}{r_I} e^{-2\mu_d(\lambda)z_d} \tag{3}$$

We have thus acquired, with Eq. (3), the absorption characteristics of the dermis layer only. The absorbance spectrum of the dermis is closely represented by coefficient $\mu_d(\lambda)$ because of the weak wavelength dependence of scattering.

It is known that the superficial epidermis layer, owing to its pigment content, is the dominant source of NIR absorption. Because of the absence of blood, however, the epidermis yields no useful information for glucose monitoring. With the invented method we can acquire solely the absorbance spectrum of the dermis layer by rejecting the absorptions of the epidermis and the subcutaneous tissues. An additional advantage is from the fact that dermis exhibits less temperature variation compared to the epidermis. It is known that surface temperature variation causes shifts of water absorption, hampering glucose monitoring.

In the above discussion it has been assumed that the pass band of the tunable filter is broad enough to facilitate the coherence gating and at the meantime narrow enough to resolve the characteristic glucose peaks. Let us now examine whether the assumption is reasonable and practical.

It is known that some predominant glucose absorption peaks reside in a wavelength range between 1 and 2.5 microns, as shown in Fig. 3. The width of these peaks are approximately 150 nm. To resolve the peaks let us choose the bandwidth of the tunable

bandpass filter to be around 30 nm. The depth resolution (gating ability) is determined by the following equation:

$$\frac{2\ln(2)}{\pi}\frac{\lambda_o^2}{\Delta\lambda}=60\mu m \tag{4}$$

The thickness of the epidermis is typically 0.1 mm and that of the dermis typically 1 mm. The above analysis (Eq. (4)) indicates that the coherence gating technique described above can comfortably resolve both the absorption peaks and the skin layers. It is therefore feasible to isolate the absorbance spectrum of the dermis layer from the epidermis and the subcutaneous tissues.

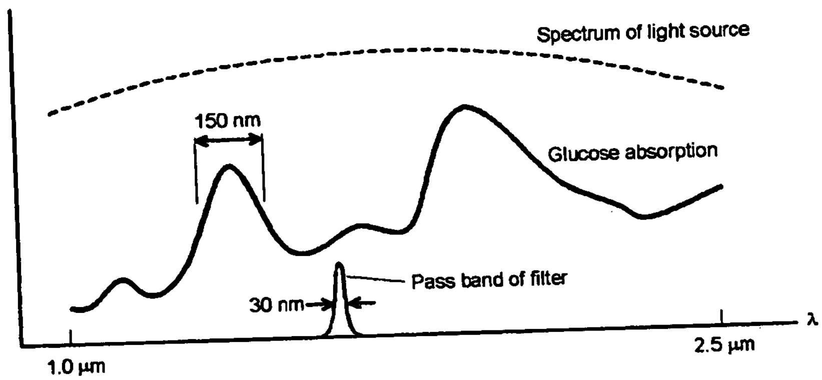


Figure. 3

To acquire the absorbance spectrum of the dermis layer one may operate the apparatus shown in Fig. 2 in this sequence: 1) locate the mirror at *I'* so that its distance matches the interface separating the epidermis and the dermis layers (position *I*); 2) scan the tunable bandpass filter across the span of the glucose signature peaks while recording the amplitude of the light intensity oscillation so that Eq.(1) is acquired; 3) relocate the mirror to *II'* so that its distance matches the interface separating the dermis and the subcutaneous tissues (position *II*); 4)repeat the process of step 2) so that Eq.(2) is also acquired. The absorbance spectrum of the dermis can be found by using Eq.(3). It should be appreciated that additional signal processing is necessary in order to determine the glucose concentration from the measured absorbance spectrum of the dermis.

The tunable bandpass filter can be one of the following devices: an electro-optically tunable filter, a rotatable fixed bandpass filter or a rotatable grating. The polarization rotators in the design can be quarter-wave plates or Faraday rotators. The movable mirror can be replace by a non-mechanical device such as a liquid-crystal cell or a combination of polarization rotators and birefringent crystals.

It should be appreciated that the use of the two detectors along with the second polarizing beam splitter, PBS2, facilitates a differential detection scheme for high signal to noise ratio. It is obvious that one can simplify the design to include a single detector with a linear polarizer.

2. Embodiment with Non-polarized Beams

It is not necessary to arrange the polarization of the light beams in the way described above. An alternative optical configuration for the same purpose is shown in Fig. 4. In this design the polarizing beam splitter is replaced by a non-polarizing beam splitter. The polarization states of the light beams can be arbitrary. With this design, however, only half of the light energy reaches the detector.

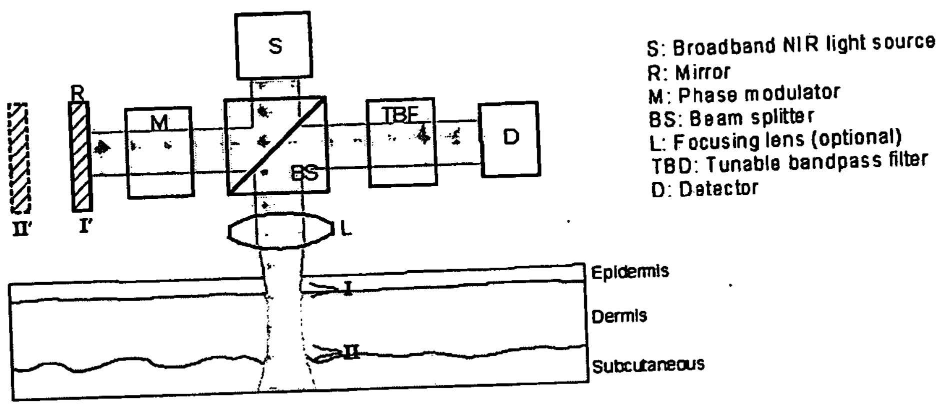


Figure 4

3. Embodiment with Detector Array

The absorbance spectrum can also be resolved by a dispersive device and a detector array instead of the tunable bandpass filter. In the design shown in Fig. 5, a reflective grating is coupled with an array of detectors. With this design the speed

of data acquisition can be substantially increased through parallel processing. This design can also be reconfigured to accommodate polarized light beams, similar to what shown in Fig. 2.

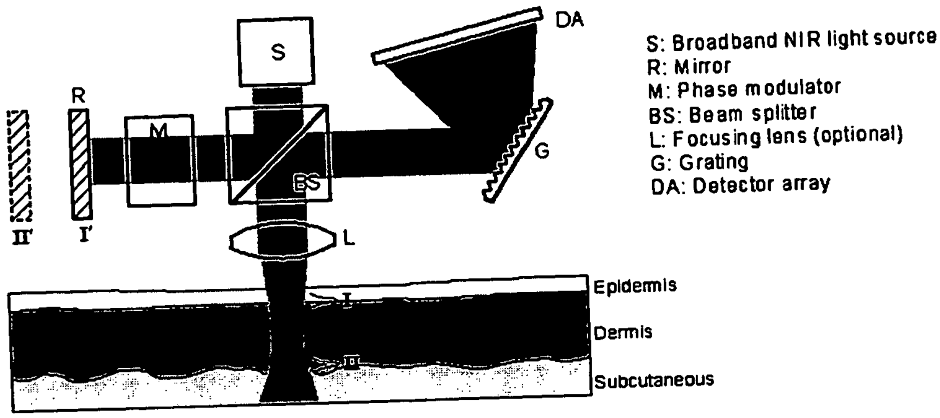


Figure 5

4. Embodiment without Spectrum Analyzer

The absorbance spectrum of the substances may also be acquired by means of post-detection signal analysis without the help of a tunable bandpass filter or a grating with detector array. This simplifies the design shown in Fig. 2 to that in Fig. 6. The same simplification can be applied to the non-polarizing version shown in Fig. 4.

Without a spectrum analyzer the absorbance spectrum of the tissues may be directly calculated from the intensity oscillation created by the interfering beams of the whole spectra. Certain mathematical transformations, such as a suitable wavelets transformation, may be adopted for such task.

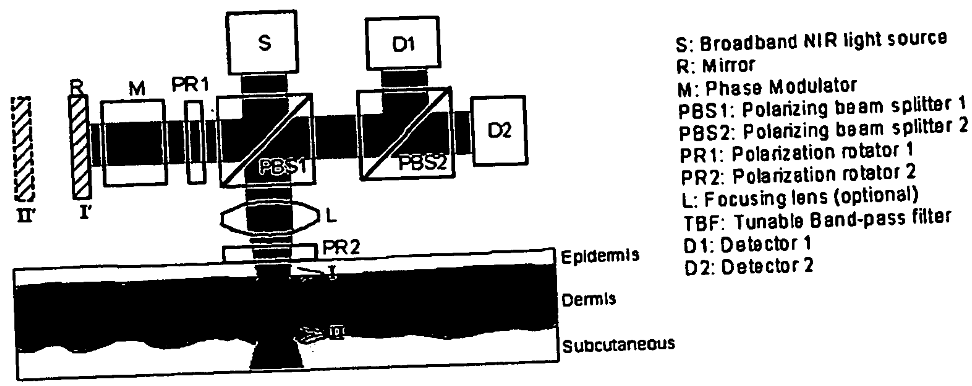


Figure 6

[0059] Only a few implementations are disclosed in this application. However, it is understood that variations and enhancements may be made. As an example, the device in FIG. 2 on page 24 may have a second waveguide different from the waveguide 272 to direct both of the beams from the optical probe head 220 to the modulator 250 and the detection subsystem 260. In this design, the light director 210 may be eliminated.

Claims

What is claimed is what is described in the text and illustrated in the drawings, including:

1. A method, comprising:

guiding optical radiation in two optical modes through an optical waveguide towards a sample;

directing radiation associated with one of the two modes to interact with the sample without allowing the other mode to reach the sample;

collecting light reflected or backscattered from the sample;

guiding optical radiation in the two modes through an optical waveguide to an optical detection module;

converting the optical radiation in the two modes, at least in part, to a pair of new modes in the optical detection module; and

detecting the intensities, including their temporal and spectral variations, of the pair of new modes to extract information about the sample.

2. The method as in claim 1, further comprising adjusting the relative optical delay between the two modes to generate intensity variation in the third mode.

3. The method as in claim 1, further comprising tuning the spectral distribution of the light radiation in said two modes to selectively measure one or more spectral components within the sample.

4. The method as in claim 3, wherein a tunable bandpass filter is used to perform the tuning.

5. The method as in claim 1, further comprising usingat least one polarization maintaining fiber to guide optical radiation.

6. The method as in claim 5, wherein thetwo optical modes are two orthogonal polarization states.

7. The method as in claim 5, further comprising controlling the two modes to be a common optical mode inside at least part of the at least one optical waveguide.

8. The method as in claim 1, further comprising:

controlling the optical radiation to be in a single optical mode before the radiation reaches the sample; and

controlling the reflected or backscattered light radiation from the sample to be in an independent optical mode.

9. The method as in claim 1, further comprising:

separating optical radiation in the detection module into different spectral components; and

directing the different spectral components to different optical detectors to produce different detector outputs.

10. A device, comprising:

an optical waveguide to guide optical radiation in two propagation modes;

an optical probe head coupled to the optical waveguide to receive the optical radiation in the two modes, the optical probe head operable to (1) redirect one of the two modes back to the optical waveguide, (2)transmit the radiation in the other mode to a sample, and (3) receive and direct the reflected or backscattered radiation from the sample into the waveguide; and

an optical detection module coupled to the optical waveguide to receive the radiation redirected by the probe head and to convert the two modes, at least in part, to a pair of new modes.

11. The device as in claim 10, wherein the optical waveguide is an optical fiber.

12. The device as in claim 10, wherein the optical waveguide is a polarization maintaining fiber.

13. The device as in claim 10, further comprising a differential delay device in an optical waveguide between the optical probe head and the optical detection module to modulate the relative optical path length of the two propagation modes.

14. A device, comprising:

an optical waveguide to guide an optical radiation in a first optical mode;

an optical probe head coupled to the optical waveguide to receive the optical radiation, the optical probe head operable to (1) redirect a portion of the optical radiation back to the optical waveguide while transmitting the remaining radiation to a sample, (2) receive and direct the reflected or backscattered radiation from the sample into the waveguide, and (3) control the reflected or the backscattered light from the sample to be in a second optical mode different from the first optical mode; and

an optical detection module coupled to the optical waveguide to receive the radiation redirected by the probe head and to convert optical radiation in the first and second optical modes, at least in part, into a common optical mode.

15. The device as in claim 14, wherein the optical waveguide comprises an optical fiber.

16. The device as in claim 14, wherein the optical waveguide comprises a polarization maintaining fiber.

17. The device as in claim 14, further comprising a differential delay device in an optical path between the optical probe head and the optical detection module to modulate the relative optical path length of the two propagation modes.

Abstract

This application describes designs, implementations, and techniques for using an optical waveguide to direct optical radiation in at least one propagation mode to and from a sample to be examined. The consolidation of the different modes or of the different radiated parts in the same mode is utilized to extract information about optical inhomogeneity and other properties in the sample.

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